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Stoneware and porcelain fireplaces

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STONEWARE AND PORCELAIN FIREPLACES

BY

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I would like to dedicate this work to my wife for without her support this whole course of education would not have been possible, and to Hobart Cowles for his great patience and dedication as a teacher-potter.

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INTRODUCTION

Within the potter's fraternity it appears that no one has made public a very reliable investigation into thermal-shock resistant clay bodies which a potter would find suitable for his methods of working. This may be partly due to most potters' lack of both concern for and background in the technical science of clay. Also few potters can afford the time to research available technical data and to execute tests which might lead to solutions which can be used confidently. Since I was interested in using such a material in the future, I decided to begin establishing a working understanding of the special requirements for such a clay-based material while teacher assistance, material, equipment and technical references are available in one place.

I chose both stoneware and porcelain because they have so much in common, yet are somewhat opposites in many ways. Each could reveal insights, aesthetically and technically, which might suggest potential solutions or areas to avoid in regard to the other which might not be discovered had only one type of clay been investigated.

I felt such a study would be beneficial also because special adjustments in glazes are required so that they will fit and expand at the same rate as the body when heat is suddenly applied. It also seemed likely that new types of glazes might develop as lithia and other low expansion materials were present in high quantities.

In deciding to concentrate on fireplaces I was merely finding a very critical technical requirement for flame-ware durability. The fireplace, however, also allowed me to move out of the area of functional serving and eating vessels with which I already had some familiarity. I tend to think of the firepot as being a part of a category of industrially designed ceramic furnishings and fixtures which have become very sterile as household objects. The items of this category (firepots, sanitaryware, large planters, fountains, etc.) tend to be rather large and monolithically structured items which often contain non-ceramic hardware. They also share the function of controlling natural elements such as water, fire, air, earth and processes involving them. It is the common problems which large, monolithic structures present in terms of designing, constructing, drying, and firing with which I wanted to become familiar.

My whole orientation, then, was an effort to begin serious preparation for lifelong involvement in two very specialized areas of ceramics through a single problem.

CHAPTER I

CERAMIC THERMAL ENDURANCE

> There are many factors affecting thermal endurance of vitrified ceramic compositions, but where such factors as size of the specimens, method of preparation, and method of testing are the same, the intercomparison becomes less complex. Thermal endurance of similar bodies depends primarily on three physical properties, namely: thermal conductivity, thermal expansion, and physical strength. A low thermal conductivity is inherent in most ceramic compositions. When specimens are exposed to sudden temperature changes, a sharp thermal gradient rises. This in itself is not serious but it is accompanied by temperature-induced volume changes producing large stresses within the specimen. In a composition which has a positive thermal expansion, an increase in temperature causes the body to be placed in compression. As the compressive strength of most ceramic compositions is high, such specimens rarely fail on heating. On subjecting this specimen to a sudden lowering of temperature, the surface becomes subjected to tensile stresses, and, as the tensile strength is relatively low, specimens fail quite readily. Hence, the lower the thermal expansion the less severe will be the tensile stresses on cooling. Thus, one of the objectives in the search for high thermal endurance has been to develop compositions with low thermal expansion.[1]

This quote expresses the conclusions I have reached in looking back over many reading and test results. It seems that the most consistently agreed upon criteria for thermal

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[1] Edward J. Smoke, "Ceramic Compositions Having Negative Thermal Expansion," Journal of the American Ceramic Society, Vol. IV, (March, 1951) p. 87.

endurance[2] are rapid thermal conductivity and dispersion, low thermal expansion, and high physical strength. Since there are consistent suggestions for increasing physical strength of ceramic materials, this is perhaps the best place to begin.

Porosity and strength

It has been concluded that porosity in ceramics weakens the fired product. Porosity is the result of empty voids, or pores, which lie between clay, silica, and non-clay mineral grains. Hall states that pores act as stress concentrators between these grains, and it is from here that cracks are nucleated. Pore shape, pore orientation, location of pores (within the grain itself or between the grains' surfaces), and open versus closed pores are all variables which directly affect strength.[3]

Porosity is affected by the ratios of different grain sizes and the temperature to which the body is fired. Assuming maximum body temperature is reached, it can be said that a predominantly course-grained body is weakest since

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[2]The ability of a ceramic material to withstand repeated sudden heatings and coolings, and uneven heatings and coolings.

[3]Richard C. Hall, "Strengthening Ceramic Materials," American Ceramic Society Bulletin, Vol. XLVII, (March, 1968), pp. 251.

large grains do not compact nor melt as readily as fine grains and thereby create voids. These large grains also normally do not have strong bonds between themselves which are necessary to hold them together under stress.

It has been proven by several sources identified by Hall, that the finer the grain size of all the materials in the clay, the stronger both the unfired and fired body. Research has shown that cracks and ruptures, which all solid materials contain, are interrupted, or resisted by each grain boundary (the joint bonding two grain surfaces to each other).[4] Small grains pack together tightly, and touch more of their total surfaces to surrounding grains, which in turn minimizes voids and decreases the porosity that weakens the ceramic.

Thermal conductivity

A by-product of fine grain size and the absence of pore gaps is an increase in the rate of thermal conductivity and dispersion. If more grains are in contact with each other over a greater amount of surface area per grain, it follows that heat can be transferred from one grain to the next more rapidly. This permits all of the grains to expand more thoroughly and quickly, which minimizes the tendency in ceramics for the area being heated to expand

[4] Hall, p. 252.

rapidly while unheated areas are unaffected. It is this uneven change in volume which creates stress between grains that causes breakage.

Use of fine-grained clay bodies has the disadvantage of causing great drying and firing shrinkage. Shrinkage, the chief cause of cracking and warping, results when water escapes in the drying process and when heat causes changes in the body during firing. These processes cause the clay particles to pack together tightly. As a maturing temperature is reached in firing, melting of the outside surface of each grain occurs and the resultant liquid flows into the open pores. This causes the grains, now smaller in size, to pack even closer together. Figures 1-3 illustrate this process in cross sectional view.

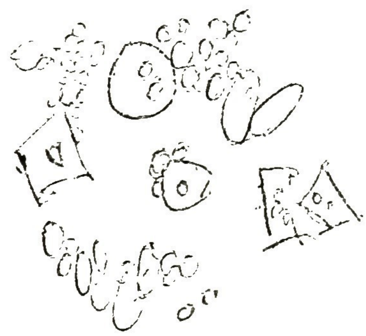

Figure 1.
Clay particles suspended in water. Note pores within grains.

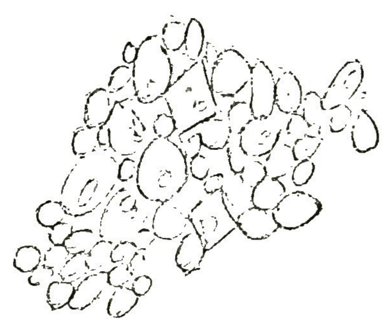

Figure 2.
Dry clay containing air gaps and some water.

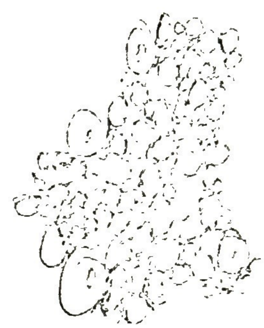

Figure 3.
Fired ceramic of liquid glass and bonded crystals.

Ware and Russell suggest in research they conducted that fired shrinkage can be counteracted, if materials which actually expand during firing are added to the body.[5] Swelling of each of the added grains counteracts the shrinkage and stress of the rest of the body. They tried using spodumene, kyanite, mullite, topaz, pyrophyllite, dumortierite, and other materials known to expand on firing. Only spodumene and kyanite worked very well, but they are suspected of having a sudden, critical point of expansion like quartz and cristobalite which could cause rupturing of the body. This expansion also causes an increase in porosity because as each grain swells it creates voids both within itself and around itself by pushing other grains away. The study found, however, that barium silicate and kyanite added together caused early melting and a 'gradual' expansion which filled internal and external voids while reducing shrinkage. Final products of this fired reaction are celsian and mullite according to this report.

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[5] Robert K. Ware and Ralston Russell, Jr., "Porcelain Having Low-Firing Shrinkage," American Ceramic Society Bulletin, Vol. XLIII, (May, 1964), p. 384.

Thermal expansion and thermal endurance

As long as heat is applied evenly and somewhat moderately to fired ceramic material, fine grain size and good thermal conductivity are sufficient to overcome breakage. If applied suddenly or intensely, failure can be expected. When fired to maturity, all clay bodies form mullite, fused silica, and mixed flux-alumina-silica solid solutions which when cooled form crystalline networks and amorphous glass. When re-heated, expansion takes place according to the thermal coefficients of the clay body's various crystalline and glassy components.

If the temperature is raised above 200-250°C, alpha-cristobalite crystals suddenly expand to form beta-cristobalite which causes a great deal of stress. Further heating to 573°C causes a sudden expansion of all alpha-quartz into beta-quartz.[6] If heating is too rapid, and if these critical temperatures are passed through suddenly, then expansion will happen instantly and the overwhelming stress created in the grain boundaries will break the ceramic.

There are some writers who suggest that if fired high enough, the cristobalite and quartz will all melt into fused silica which when cooled has very slight contraction-expansion

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[6] Ernst Rosenthal, Pottery and Ceramics (Middlesex, England, 1949), p. 73.

properties. This material is one of the lowest expansion materials known and is considered an ideal standard. In practice this melt is impossible to achieve completely in formed ware, and loss is costly and frequent. Usually only the surface of larger quartz grains are melted, and when re-cooled the unmelted core of each grain retains its original coefficient of expansion. While this is believed to be the 'strongest' body possible by a few researchers, it is not suitable for 'thermal shock resistant' bodies.[7]

It is well known that silica crystals can be stabilized and coefficient of thermal expansion reduced when reacted with low expansion materials. Alumina, the second most abundant element in clay bodies, reacts with silica to form mullite which is low in expansion. There are several theories about mullite's influences on body strength, but most can be proven inconclusive.[7] Additions of kyanite, andulasite, sillmanite, dumortierite, or calcined mullite (formed by pre-firing any of the former materials) are materials which supply additional alumina to the body. All of these alumina-silica bodies require very high temperatures and porosity is always quite high. I have found additions of mullite helpful as an additive, but kyanite contributed little.

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[7] László Mattyasovszky-Zsolnay, "Mechanical Strength of Porcelain," Journal of the American Ceramic Society, Vol. XL, (September, 1957), pp. 299-306.

Fluxes and other modifiers such as magnesia, zirconia, titania, beryl and other low expansion materials are available but not practical for the potter because of expense, instability, lack of significant effectiveness, and criticalness of maturing temperature.

Effect of lithium on shock resistance

> Compositions having negative linear thermal compositions ranging form 0 to -0.38%, have been obtained in two areas of the system lithia-aluminum-silica. Petrographic and x-ray examinations indicate the presence of three principle crystalline phases, each of which is a solid solution: beta-eucryptite, beta-spodumene, and an unidentified quartzlike phase. All compositions were prepared from lithium carbonate, clay, flint and alumina. Some compositions have been prepared which, for all practical purposes, exhibit no change in length when heated from room temperature to as high as 600°C. Some of these compositions have excellent thermal endurance, withstanding repeated quenchings from a temperature of 1100°C into water at room temperature.[8]

From research material, it appears that lithia and alumina assimilate silica quite easily and form molecules which are thermally stable. Eucryptite is a crystal with the molecular formula $Li_2O:Al_2O_3:2SiO_2$ (1:1:2) which can assume one more atom of silica to become $Li_2O:Al_2O_3:3SiO_2$ (1:1:3). When heated these materials contract instead of

[8]Edward Smoke, "Ceramic Compositions Having Negative Linear Thermal Expansion," Journal of the American Ceramic Society, Vol. XXXIV, (March, 1951), p. 87.

expanding, a phenomena referred to as a negative expansion (Fig. 4). This information led me to pursue further research, as I assumed that this contraction could balance expansion of other materials as is done to correct a crackle in glazes. I found that eucryptite is very expensive, however, and hard to find on the market. One author also reports that eucryptite bodies are very weak structurally because of the shape of the crystal and because of the inferior ionic bonds which it forms with other molecules.[9]

With this in mind, I turned to the very inexpensive material, amblygonite, to achieve the same result. A lithium fluoride-aluminum phosphate material, amblygonite contains but one percent of silica and negligible iron. In the presence of free silica, it seemed possible that eucryptite ratios might be developed.

The main problem in this reasoning is the lack of information on the role of fluorine and phosphorous in ceramics. Phosphorous can be a glass former, or a network former; it may or may not have a critical expansion point; and it seems to melt suddenly. Further, it may prevent any eucryptite qualities from resulting, or it may cause spodumene behavior.

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[9] E. A. Bush and F. A. Hummel, "High-Temperature Mechanical Properties of Ceramic Materials: II, Beta-Eucryptite," <u>Journal of the American Ceramic Society</u>, Vol. XLII, (August, 1959), pp. 388-391.

In my own tests amblygonite seems to behave like bone ash does in bone china. Each seems to be very color sensitive to iron, producing cream colors in whiteware and red-oranges in stoneware. Likewise, a sudden melting point results from using too much of these materials. Whiteware bodies RL 13-18 and stoneware bodies APG-A 1&2 and FA-1&2 all reveal these factors.* Before enough amblygonite could be added to assimilate all of the free silica to counteract the thermal expansion, bloating and eutectics were encountered. This made using amblygonite as the primary flux at cone 9 very difficult.

Alpha-spodumene, petalite, and beta-spodumene glasses

> It is evident...that the silica exsolved from metakaolin as it converts to mullite is assimilated by beta-spodumene ($Li_2O:Al_2O_3:4SiO_2$) to produce beta-spodumene solid solutions of a composition lying between $Li_2O:Al_2O_3:4SiO_2$ (1:1:4) and $Li_2O:Al_2O_3:8SiO_2$ (1:1:8). Petalite already contains 8 moles of silica and can theoretically accept no more into solid solution. The persistance of cristobalite and beta-quartz in the petalite-kaolin composition is thus understandable.[10]

This quote is from a study of a pure kaolin body, and bodies to which either spodumene or petalite were added.

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*See Appendix A and B for complete information.

[10] J. H. Fishwick, R. R. Van Der Beck, and R. W. Talley, "Low Thermal Expansion Compositions in the Systems Spodumene-Kaolin and Petalite-Kaolin," American Ceramic Society Bulletin, Vol. XLIII, (November, 1964), p. 832.

All researchers indicate rather consistently that beta-spodumene has a thermal expansion ratio just a little higher than fused silica, but when more silica is assimilated, it expands less (1:1:6 lithium orthoclase) or almost not at all (1:1:8 petalite). Contrary to popular belief, petalite is a

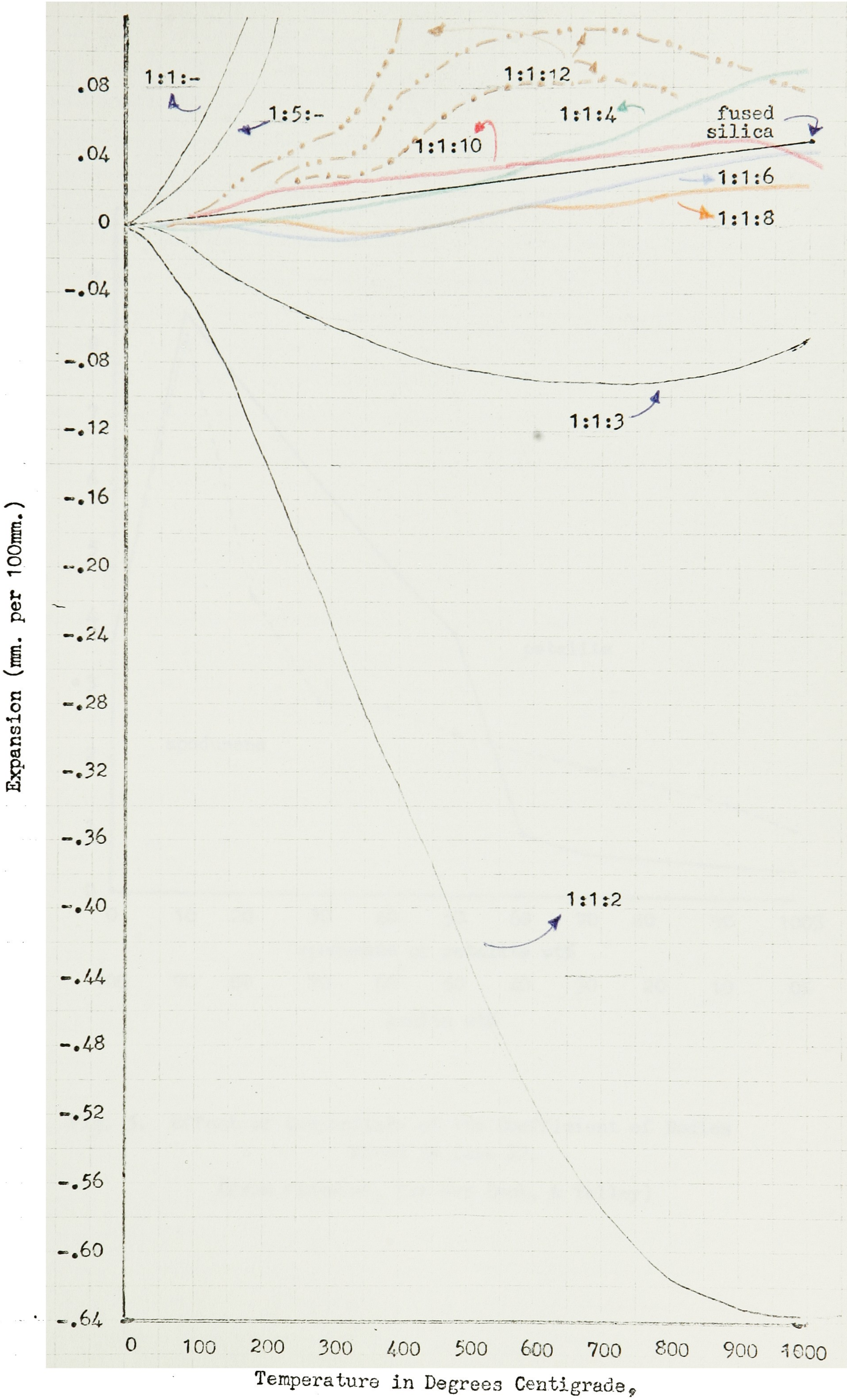
$$\underset{\text{spodumene}}{Li_2O:Al_2O_3:4SiO_2} + \underset{\text{meta-kaolin}}{3(Al_2O_3:2SiO_2)} \rightarrow \underset{\text{petalite}}{Li_2O:Al_2O_3:8SiO_2} + \underset{\text{mullite}}{3Al_2O_3:2SiO_2}$$

poor material to use to counteract thermal expansion because of its very poor ability to assimilate 'any' free silica from the clay. What results are ratios 1:1:10 and 1:1:12 which are very unstable and which readily permit a breakdown to petalite, cristobalite and quartz when re-heated a few times (Fig. 4).

Each clay has its own minimum lithium-additive requirement which is a function of the silica-alumina ratio of that clay. EPK (kaolin) has a low silica-high alumina ratio. Fishwick and associates found that in practice, 10% additions of spodumene and petalite to EPK caused the body to develop maximum expansions. When 20% additions of spodumene were made, expansion ratios decreased rapidly, and leveled off at 30%. Petalite followed a similar pattern but much more gradual, requiring more petalite to achieve a minimum. Free silica was absent from the body with 20% additions of spodumene but was still present in the 30% petalite body (Fig. 5).

Figure 4

Thermal Expansion of Synthetic Lithium Minerals (from Hummel).



.08
.04
0
-.04
-.08
-.12
-.16
-.20
-.24
-.28
-.32
-.36
-.40
-.44
-.48
-.52
-.56
-.60
-.64
Expansion (mm. per 100mm.)
0
100
200
300
400
500
600
700
800
900
1000
Temperature in Degrees Centigrade.
1:1:-
1:5:-
1:1:12
1:1:10
1:1:4
fused silica
1:1:6
1:1:8
1:1:3
1:1:2

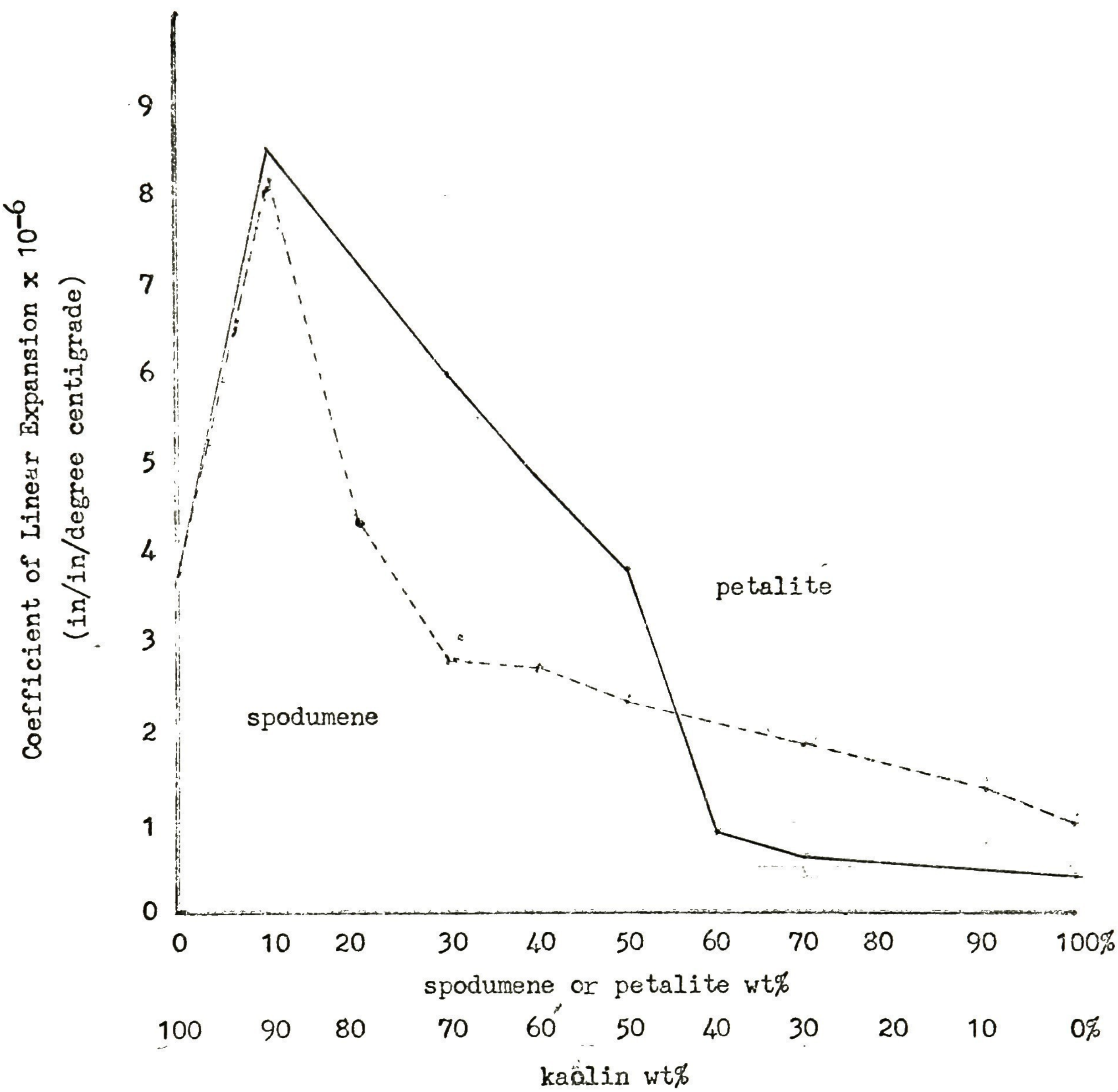


Fig. 5. Effect of Composition of the Coefficient of Bodies Fired to Cone 12.

(from Fishwick, Van Der Beck, & Talley)

Shrinkages were off-set, according to this study, which concurs with earlier remarks. When heated to 700-1000°C, alpha-spodumene (naturally-occurring spodumene) expands irreversibly in volume to form beta-spodumene. Petalite expands to a lesser degree in the same temperature range to form beta-spodumene and free silica which recombine to form beta-spodumene solid solutions at maturing temperatures. When cooled, the spodumene bodies revealed a marked shrinkage reduction over the petalite bodies.

An extra benefit of lithium glasses is an increase in physical strength of the kaolin bodies. Additions of 10-20% spodumene and 30-40% petalite tended to maximize strengths although this tends to vary with temperature. Further additions of either mineral increases grain size growth rate which causes porosity and decreases strength.

CHAPTER II

BODY FORMULATION PROCEDURES, RESULTS, AND CONCLUSIONS

Shock resistant porcelain

Using this research data as a guide (not as a rule) I began testing whiteware bodies* on the basis of a porcelain body which a previous instructor had given me. Since we lacked some of the materials called for, substitutions were made but the body didn't work very well. The thixotropic condition created by the alkali minerals required more ball clay to hold it together and make it stiffer. Before this the body behaved very much like bread dough and had the same consistency. When the additions had been made, the total clays comprised 50% of the body.

The first nine samples were made to learn the effect of reducing flint, and then the feldspars also, while petalite was increased in their place. In general, the absorptions were zero as long as nepheline syenite was present at 5% with dolomite at 2%. Some samples endured heat shock tests,

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*Complete charts on composition and results of the RL-whiteware series appear in Appendix A.

even with flint included. Because of the thixotropic problem it created, and what I found in research against it, I stopped testing petalite.

Thixotropy and solubility seemed to be inherent with all the lithia minerals, some being worse than others when sufficient quantities are added to prevent thermal shock failure. When the first eight samples were dried, a very hard crust formed on the outside which was hard to scratch. On the inside, the sample was soft but badly cracked. When fired, the surfaces of the sample formed deep cracks and were cream colored and porous. The conclusion we reached is that soluble salts are carried to the surface as the sample dries out, and are deposited there when the water evaporates. When fired, this surface concentration of salts reacts to develop a more mature body than is formed in the interiors. Uneven contraction results on cooling, causing the more mature external body to shatter itself over the less developed interior.

In substituting spodumene for petalite this characteristic ceased and cracking was reduced. While these samples threw well, they had a cream color and very high porosity. Since the research materials suggested less spodumene was necessary, and since spodumene is one-third lighter than petalite, it was used in lesser amounts. I then substituted amblygonite for spodumene in still lesser amounts, and found that over twenty parts with bone ash and nepheline syenite bloated and melted suddenly. At twenty parts, however, it endured heat shock tests very well. Bone ash was being used to replace the magnesia from dolomite, to avoid its incompatibility with lithia which one researcher reported. Since these bodies were cream in color and had critical melting points, I decided to substitute lepidolite for both amblygonite and nepheline syenite.

I anticipated that lepidolite would have a high melting point since its $RO:R_2O_3:RO_2$ ratio is close to spodumene's. Used alone or, as I later tried, with amblygonite, bloating occurred. These bodies were not shock resistant and burned a very gray-brown, toast color.

Having failed to get a white shock resistant body, I tried using mullite, kyanite, and extra-fine silica in a body containing thirty-five parts of lepidolite, and in a body containing twenty parts lepidolite with fifteen parts amblygonite. The 35-mesh mullite and 100-mesh mullite seem to produce some consistent effects of shock resistance while bleaching colors to white.

In the meantime, I combined spodumene and amblygonite in series RL-34 to 36 and found that absorptions could be lowered while shrinkages could be held to 8%. Shock resistance was very good and no firing or drying cracks occurred. The main problem was that the surface of the body was a very dark, rich brown, unlike any stoneware. Below the 'skin' the body was a very pure white color. Here again, the presence of lithia and phosphorous in a reducing atmosphere seems to multiply the effects of any trace of iron which may be present in the body.

My final whiteware tests sought to achieve whiteness and low absorptions with translucency. Combining lepidolite and petalite in various ratios to a 40% clay-20% fine-silica body, I developed an excellent series of translucent, snow-white porcelains. Zero absorptions were had, even in some with 15% mullite (100-mesh) added. Bloating did occur due to an eutectic in one series. None of these bodies were at all shock resistant.

When silica was dropped from the 38 and 39 series and fine and coarse mullite added (38b, 38c, 39b, and 39c), color remained white and absorptions low, while thermal shock and lower shrinkages were achieved. Finer meshes of mullite could bring zero absorptions, I believe.

I anticipate a series wherein the petalite would be increased from 30% while lepidolite varied from 15% to 20% to see if translucency can't be had from the high silica in the petalite mineral. Small additions of extra-fine quartz may be possible, as series RL-1 to RL-9 indicate. This might permit a boundary line to be found between translucency and thermal shock failure.

My conclusion in regards to whiteware bodies is that low shrinkage, zero porosity, good whiteness and thermal shock resistance can be achieved with a 40% clay, 40% or more lepidolite-petalite, and 0-20% fine mesh mullite body. Use of 35-mesh mullite permits stoneware qualities of handling and texture while increasing porosity and yet retaining whiteness.

I am particularly interested in lepidolite as an auxiliary flux. As a mica, it contributes excellent mixing, handling, drying and melting qualities while permitting whiteness and causing a glistening surface effect from each mica flake of the surface.

All of these materials fail to behave adequately when used as the only flux in the body. Amblygonite and spodumene permit very low shrinkages for porcelains, while retaining low absorptions but color is inevitable. This is the most shock resistant body of the whole RL-series, I believe. I feel the additions of extra-fine silica needs to be done carefully, while use of feldspars is not practical at all because mixing of lithium minerals achieves more desirable ends simultaneously. In place of silica, I believe, one might do well to investigate use of Pyrex powdered glass to achieve translucency, if the components of the Pyrex don't react unfavorably with the rest of the minerals used.

<u>Shock resistant stoneware</u>

Unlike porcelain, stonewares are coarser grained materials which tolerate a degree of porosity. I developed a stoneware body by combining A. P. Green fireclay, XX Sagger, and Tennessee #5 ball clay.* I attempted to keep the fireclay low to reduce porosity and large grained particle sizes. When drying, cracks became a problem so I increased the fire clay and added Edgar Plastic Kaolin in place of half of the ball clay.

My initial tests, however, were a series of A. P. Green - lithia mineral tests. I did this because nearly everyone using flameware bodies seems to use A. P. Green fireclay and petalite (60:40) with no additions. Spodumene, added in 10, 20, and 30% amounts, immediately rendered the body shock resistant, while increasing absorptions and decreasing shrinkages. Petalite in 25-30% additions were identical to 10% additions of spodumene except that breakage couldn't be prevented. Amblygonite or lepidolite at 20% caused

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*Complete charts on compositions and results of the stoneware tests appear in Appendix B.

bloating before shock resistance could be achieved. Spodumene and petalite created orange colors at their higher percentages; amblygonite produced rich, red-oranges; and lepidolite caused a gray-toasted brown color with pleasant speckles.

When combined together in A. P. Green, spodumene and amblygonite didn't affect shock resistance until a 15% spodumene-10% amblygonite mixture was arrived at. Lepidolite and amblygonite never worked together.

I then tried using all but petalite in my stoneware body. Each was used alone, and in combination, and the total clay was adjusted so 100 parts was always the total of everything in the body. The spodumene body at 30 parts was the only body which worked without being mixed with other lithia minerals. Porosity was very high again. The lepidolite-amblygonite bodies failed, but the bodies with 20-25% spodumene and 5% amblygonite worked well. Shock resistance, average shrinkage and porosity were noted in a very pleasant red-orange body. When made into shallow frying pans, shock resistance continued, but the body failed to endure heat when used in such tall forms as coffee pots or any large form as in the fireplace.

Suggested solutions

In order to determine what to do from here, I believe, a number of things can be done which will yield a stoneware suitable for monolithic fireplaces. First, I would reconsider the silica-alumina ratios of each clay used. Most kaolins have a very low percent of silica and rather high alumina contents, according to clay analysis from Edgar Plastic Kaolin Company and United Sierra Mines. Ball clays vary considerably while wad clays, bond clays, sagger clays, and I suspect, fireclays, have very high silica and low alumina contents. While the percentages don't seem that significant, I believe it is critical to use low silica-high alumina clays.

The next problem is proper mixing. My initial procedure was to mix spodumene and amblygonite with the blunger mixer. I let the mixture settle out to the bottom, poured off the water, added more water, and remixed. I did this three times to get rid of the soluble salts so my hands would not be attacked by them. Adding more water, I then added the ball clay and mixed until everything became a thick consistency. This mixture was then added to the dry, pre-mixed, coarser clays in the pug mill.

I now suspect that the non-clay/ball clay mix was not thoroughly dispersed into the rest of the clays in the pug mill, which caused pockets of low expansion melts surrounded by large areas of unaffected clays. The presence of large, white specks in the last fireplace I made seems to verify this suspicion. To correct this I suggest use of excesses of water in the final mixing of the lithia minerals - ball clay batch to disperse these grains thoroughly. Screening through a very fine mesh screen could further break down lumps or even mixing the whole batch of clays and minerals entirely as a slip might be necessary. Use of extra fine-mesh spodumene and amblygonite could also improve dispersion and melting in the firing itself.

Should use of low silica-high alumina clays and thorough mixing procedures fail to achieve zero thermal expansions, it may be advisable to reduce the quantity of fireclay and/or replace it with coarse and medium mesh mullite. Further additions of spodumene or amblygonite in fine meshes may then be necessary if this fails.

Unless zero expansion is achieved, I believe failure is going to occur in a piece as large and as thick as a fireplace. Large grained clays typical of stoneware may have an inherent high thermal expansion within each grain itself. This is why I have suggested using mullite instead. If these suggestions fail completely, my only solution is to line the fireplace with a lining of fire resistant concrete or with a refractory castable.

CHAPTER III

HIGH-FIRE GLAZES SUITABLE FOR THERMAL SHOCK RESISTANT CLAY BODIES

A discussion of glazes tends to be far more elaborate than that for clay bodies because the former has such a great potential of ingredients; each of which contributes a pronounced effect in the final fired product. Likewise, other factors also change the final result, such as the oxidation-reduction factors of firing, temperatures reached, cooling cycle, and even the components of the body which the glaze is being fired on.

Since the statements in regard to the lithia-alumina-silica system continues to hold true for glazes, I continued to research the previous studies for further indications of what might be expected when developing glaze compositions. By utilizing a triangular phase diagram (Fig. 6), one can determine three binary systems (alumina-silica, lithia-alumina, lithia-silica) and the ternary components of the lithia-alumina-silica system. Each side of the triangle is a binary system because the third element totals zero. Moving from the edge into the interior of the triangle, one can explore the ternary compounds and can determine the exact percentage of each element present.

Figure 6

The Ternary System $Li_2O-Al_2O_3-SiO_2$

(After Murphy & Hummel)

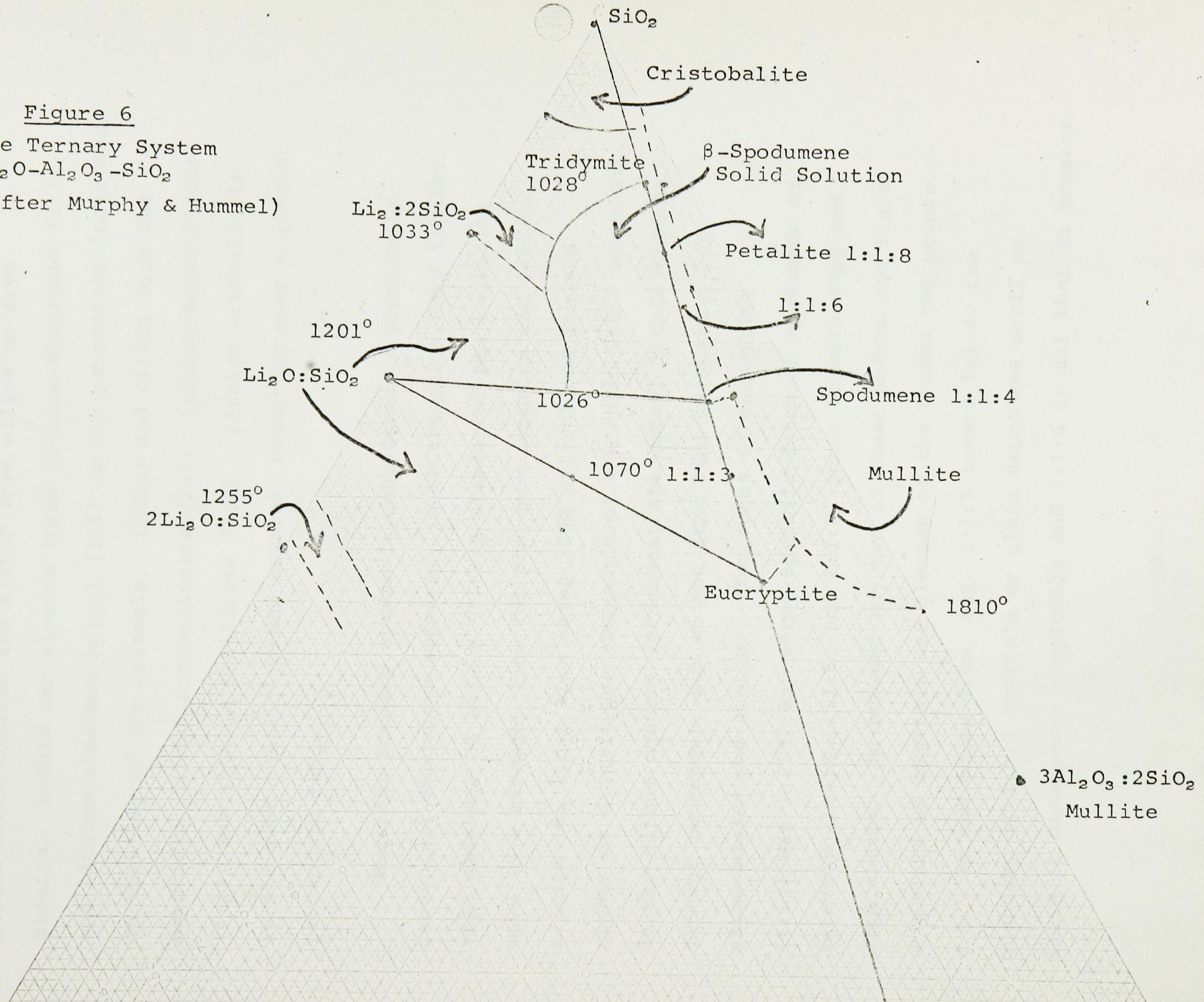


Figure 6 indicates that the binary system alumina-silica forms mullite and either free silica or free alumina. Lithia and alumina forms lithium-aluminate (1:1), and lithium aluminum spinel (1:5) in the percentage indicated on that leg of the triangle. Lithia and silica form the materials lithium orthosilicate (2:1), lithium metasilicate (1:1), and lithium disilicate (1:2). Lithium metasilicate is the most readily formed crystal, occurring over a greater percentage range.

When the ternary system is considered, a peculiarly convenient phenomena appears. If at the point $23\frac{1}{2}\%$ lithia: $76\frac{1}{2}\%$ alumina: 0% silica (lithia aluminate) one begins to move in a straight line for the apex opposite the lithia-alumina leg (that apex being 100% silica) one finds a number of significant compounds of the ratio 1:1:? occurring. As the silica content increases, the actual lithia-alumina content decreases, but at the same time maintain a 1:1 ratio toward one another. Two forms of eucryptite (1:1:2 and 1:1:3) and three specific forms of spodumene of interest (1:1:4, 1:1:6, and 1:1:8) occur between $47\frac{1}{2}\%$ and $79\frac{1}{2}\%$ silica. In between any two of these points one finds a mixture of crystals and glasses of the chosen two points, e.g., as one moves from, say, 1:1:3 toward 1:1:4, the quantity of 1:1:3 crystals or glass decreases until at 1:1:4 it disappears completely and 1:1:4 is all that is present.

As one moves beyond 79½% silica, beta-spodumene and cristobalite are found in solution together, and the negative thermal expansions of beta-spodumene suddenly becomes more and more irradic until it becomes positive due to the increase of cristobalite.

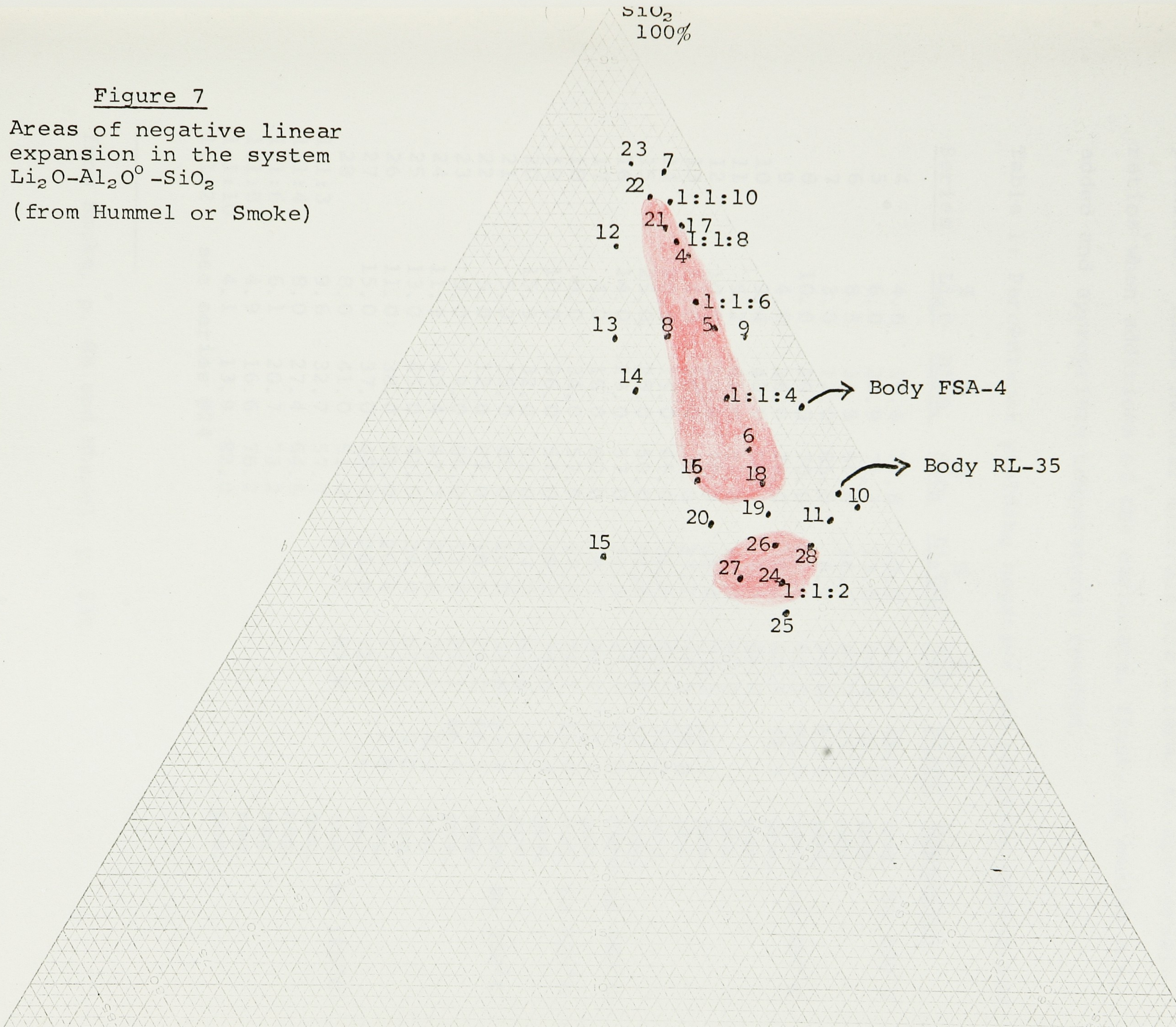
When one moves to either side of the straight line, one finds increasing occurrence of other types of crystals and glasses in the mixture. Moving to the right of the line one finds that the decrease in lithia content permits the excess alumina-silica content to form mullite in solution with the ternary compound on the line. To the left of the line, one finds the deficiency in alumina permits lithia-silica compounds to become greater and greater in the melt. Upon cooling, the mixture of materials devitrify into the amount of different crystals that the ratios of the lithia-alumina-silica will permit. Each type of crystal then acquires the expansion ratio and other physical properties inherent to that crystal. Figure 7 and Table 1 indicate the exact regions of negative and positive expansions, and Figure 8 indicates the expansion curves for ratios on the edge of the negative fields.

These results are very nearly consistent whether one begins with lithium carbonate, flint and kaolin, or with the natural alpha forms of the minerals eucyptite, spodumene, or

Figure 7

Areas of negative linear expansion in the system Li_2O-Al_2O^o-SiO_2

(from Hummel or Smoke)



petalite. These natural minerals are altered to appropriate ratios when additions of the carbonate, flint, or kaolin are added and appropriate temperatures reached.

Table 1: Percentages yielding negative and positive expansions.

Series	% Li_2O	% Al_2O_3	% SiO_2	% Li_2CO_3	% EPK	% Flint	Expansion
4	4.6	16.6	77.8	10.0	41.8	48.2	neg. to 400°C
5	6.0	22.9	71.1	13.0	54.5	32.5	neg.
6	8.5	31.5	60.0	16.6	67.7	15.8	neg.
7	3.0	12.0	85.0	6.7	29.8	63.5	pos.
8	10.0	20.0	70.0	20.0	44.0	36.0	zero to 450°C
9	4.0	26.0	70.0	8.4	60.3	31.3	pos.
10	2.4	43.0	54.6	5.0	95.0		pos.
11	5.2	41.6	53.2	10.0	90.0		pos.
12	10.0	12.0	78.0	20.6	27.3	52.1	pos.
13	14.0	16.0	70.0	27.1	34.1	38.8	pos.
14	20.0	15.0	65.0	36.2	30.0	33.8	pos.
15	25.0	25.0	50.0	41.8	46.0	12.2	pos.
16	14.0	29.0	57.0	25.9	59.1	15.0	zero to 460°C
17	4.0	16.0	80.0	8.7	39.4	51.9	pos.
18	9.0	34.0	57.0	17.3	72.1	10.6	neg. to 425°C
19	10.0	36.0	54.0	18.3	75.8	5.9	pos.
20	15.9	32.0	53.0	27.2	63.8	9.0	pos.
21	5.0	15.0	80.0	10.8	35.8	53.4	zero to 350°C
22	5.0	12.0	83.0	10.9	29.0	60.1	neg.
23	5.0	9.0	86.0	11.0	22.1	66.9	pos.
24	11.9	40.4	47.7	22.6	75.1	2.3	neg.
25	13.0	45.0	42.0	24.0	67.0	9.0	neg.
26	11.0	38.0	51.0	20.4	77.0	1.9	neg.
27	15.0	37.0	48.0	26.8	72.7	.5	neg.
28	8.0	41.0	51.0	15.2	84.0		neg. to 125°C
1:1:3	9.6	32.7	57.7				neg.
1:1:4	8.0	27.4	64.6				neg.
1:1:6	6.1	20.7	73.2				neg.
1:1:8	4.9	16.6	78.2				neg.
1:1:10	4.1	13.9	82.0				pos.
1:1:2	see series #24						

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from Smoke, p. 88 and Hummel, p. 236.

The importance of the foregoing is that one can predetermine from these phase diagrams what a given ratio of raw materials will produce when matured with heat. This is helpful in adjusting the glaze to the expansion of the body, which, because of its low lithia relative to high alumina silica content (Figure 7) and insufficient mixing and rate of reaction, probably will not exhibit negative

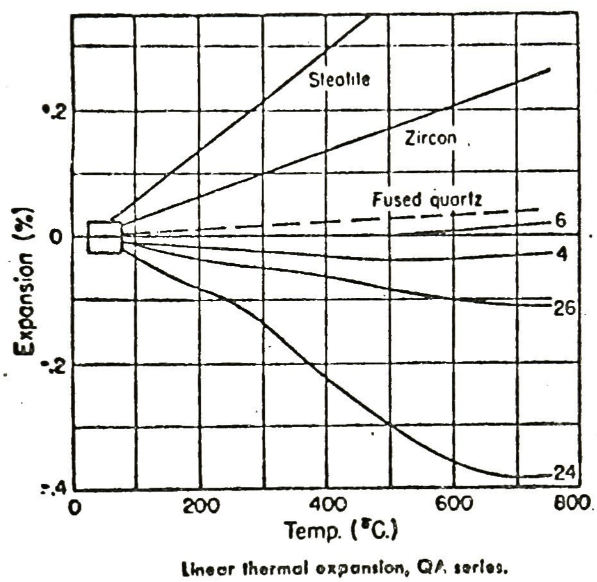

Figure 8. Expansion curves for compositions lying on edges of negative expansion fields. (from Smoke, p. 90)

expansions. Since it is the high alumina content of the clay which causes it to be refractory, it will probably be difficult to get a glaze with the same expansion simply by using the same ratios calculated for the body. It then seems reasonable to consider using other oxides in the system to arrive at a suitable 'fit' on the body.

Glaze testing procedures

In developing glazes for my own use, I attempted to compare the effects of each of the lithia minerals when added to a constant ratio of other materials. I thought I would have a large quantity of lithia present in most cases, but this was not true, as the empirical formulas for these initial tests would bear out (Figure 9).

When the results of these tests were analyzed, each was changed to improve various qualities and to overcome defects. Soon a pattern of defects began to appear. Lithia contents continues to accentuate any iron present in the clay body or glaze materials, to a point of

Figure 9. Initial glazes tested

	WA	WL	WS	WP
Amblygonite	40			
Lepidolite		40		
Spodumene			40	
Petalite				40
Whiting	20	20	20	20
Ball Clay	20	20	20	20
Flint	10	10	10	10

	BaA	BaL	BaS	BaP
Amblygonite	20			
Lepidolite		20		
Spodumene			20	
Petalite				20
$BaCO_3$	20	20	20	20
Flint	20	20	20	20
Bentonite	5	5	5	5

producing very rich red-browns on stoneware and a very cool blue-green celedon on porcelain from the same glaze (Figure 10). This is understandable from spodumene because it contains iron in its lattice which is highly active in the stoneware body, but is not so clear for the other minerals when used on porcelain.

There is also the role of the oxidation-reduction history of the firing to be considered when color and mat (crystalline)-transparent (glassy) glazes are analyzed. The presence of carbon monoxide in the reducing atmosphere joins with the clay body and glaze materials or steals oxygen from the oxides in the clay and glazes, both processes which alter the final clay and glaze composition and appearance. Likewise, the reduction of the iron and effect of lithia on the iron influences the effect of color which seems characteristic of these glazes (Figure 11-13).

Another feature of interest in these glazes is a glistening quality (Figure 10-11) which appeared on the surface of some mat glazes, and deep in some transparent glazes (Figure 14-15). In a conversation with Dr. David Pye of the Alfred University-Alfred Tech College of Ceramics and Glass, it was suggested that this may be a unique feature of lithia to come to the surface of the melting glaze at high temperatures and to volatilize into the reducing atmosphere, especially if held very long. Upon

Figure 10. Glaze WL-3b on stoneware (L.) and porcelain (R.). Glaze appears as a pale blue-green on porcelain body, is badly crackled, is very fluid, and has a very pleasant frosty translucent quality. On stoneware, even though in the same firing, the glaze is dark green where thick and rich brown where thin, is mat, almost dry in texture, and very stiff.

Figure 11. Glaze WA-7 as it appears after four separate firings. Front left test is pale orange to cream on white stoneware. Front right test is twice fired and is red-orange (thin) and green (thick) with crackle and surface glistening quality. Back left sample was once fired in last firing of front right sample. It is extremely fluid, badly crackled, transparent cream-tan color and shows glistening deep from within the glaze. Back right sample was fired in first firing of front right sample. It is dry, smooth, red-orange all over, and shows no craze or glistening.

Figure 12. Glaze BaS-9 and 10 on low iron body at right resulted in very large needle-like crystals that changes to a very fluid, pleasant green with calcia added in a rather large amount. Piece in left foreground, BaS-10 glaze, is a gray, crystalline mat that is typical of those applied to stoneware. Glaze BaS-2a-3c (rear) is the only opaque glossy surfaced glaze to be derived without opacifiers thus far. It likewise changed quality on other tests.

Figure 13. Piece on left (Bal-3c) is a frosty, satin textured, mint-green and white glaze. This glaze may shiver on Spodumeme-stoneware. On the right, BaL-3c-1 is a mat gray (thick) and brown (thin) with additions of calcia.

Figure 14. Glaze BaA-4 of cup appearing in Figure 15 crackle, color, and unique glistening quality (strange specks of light) comes from deep within the glaze.

Figure 14a. Glaze Bal-5a-5 on S.A.C. stoneware body. This glaze is like caramel, very thick and yet only slightly ready to run. On spodumene body glaze is identical to WA-7 sample (Figure 11, back left bowl) in color, glistening, and fine, fine crackle; but also has frosty bubbles like shaving lather in places.

Figure 15. Glaze BaA-3 on white stoneware (l. front) and red stoneware (l. back) and Glaze BaA-4 on white (f. right) and red (b. right) stoneware. A noted contrast in crackle can be seen, BaA-3 being very finely cracked and BaA-4 fitting on the white body while moderately cracked on the red body. BaA-3 is unaffected by iron on spodumene stoneware, being the whitest test on that body to date. It also has glistening quality to a very great degree deep in its interior on both samples.

cooling, minute lithia crystals of a significant refraction are formed when the volatilized lithia recondenses onto the surface with that lithia content which rose to the surface but did not volatilize. The occurrence of this affect, deep in the glaze seems to be answered by the fact that a high lithia ion exchange is apt to occur between the clay body and the glaze, thus creating a concentration right at the interfacing which will then form these crystals upon cooling.

The temperature reached and the amount of time taken is critical also because of the problems of fluidity, texture, and bubbles that occur. Apparently, there is a lot of reaction between the glazes I prepared and the bodies I used which created bubbles when reacting. Also, it is apparent that some of the materials are melting quite suddenly in a range between cone nine and ten (Figure 10-11). This is a problem because it is necessary to mature a glaze, that is, melt it, in order to take advantage of the suggestion of so many researchers that a glaze will strengthen a thermal shock ceramic body because as a glaze melts, it removes the surface defects and tension which can cause failure of a body before it should when reheated.

My discussions with Dr. Pye also indicated that phosphorous was the lowest melting and least chemically resistant glass former (boron, germanium, and silica are the other glass formers). There is reason to expect that it reduces the thermal coefficient of expansion in glazes, just as boron does in the sodium-calcium-silica glass known as Pyrex. Colorants used in ceramics do not necessarily produce the same hues in a phosphorous matrix as they do in a silica matrix, a factor which may account for the oranges and reds that result when bone ash or amblygonite are found in glazes. A second member of amblygonite whose behavior I did not understand was fluorine, and Dr. Pye indicated that this material is known to opacify glasses even though much of it volatilizes into the atmosphere.

Appendix D is a percentage analysis of several of the glaze analysis tests I ran which I felt revealed some valuable information. This procedure of analysis was discovered after a number of other approaches failed to provide a meaningful method of relating various characteristics. The percentage analysis procedure suggested itself while I was reading a research article utilizing this procedure. When three of four oxides are used it is very easy to plot phase diagrams for each of the various characteristics one has to deal with. By overlapping these diagrams it seems likely that one can select compositions on a percentage basis which produces the greatest number of characteristics desired. The article I was reading dealt with the quartenary system, Li_2O-Al_2O_3-CaO-SiO_2, a system which includes some of the glazes I was testing. The authors studied the effect of increasing the percentage of calcia in this system and plotted a different diagram for each percentage of calcia used (Figure 16). This graphic tool easily illustrates the clusters of percentages which form into a group of either glass or crystalline material, and moving from one diagram to the next, one can follow the effect of increasing the calcia. While these diagrams indicated the glass - crystalline regions, it would be possible to plot expansions or other qualities.

These authors' findings also adds some specific facts to my study, namely, that percentages with more than 10% lithia tend to lose low expansion and high chemical resistance along with other losses.[11] They also indicate that lithia-calcia-silica compounds can be found in solid solution with the lithia-alumina-calcia-silica compounds in melts containing 5-25% calcia. Their results are

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[11] H. W. Rauch, C. H. Common, Jr., and H. H. Blair, "Exploration of Li_2O-CaO-Al_2O_3-SiO_2 at Different Levels from 0 to 30 wt. % CaO," Journal of American Ceramic Society, Vol. XLII (March, 1959), pp. 113-120.

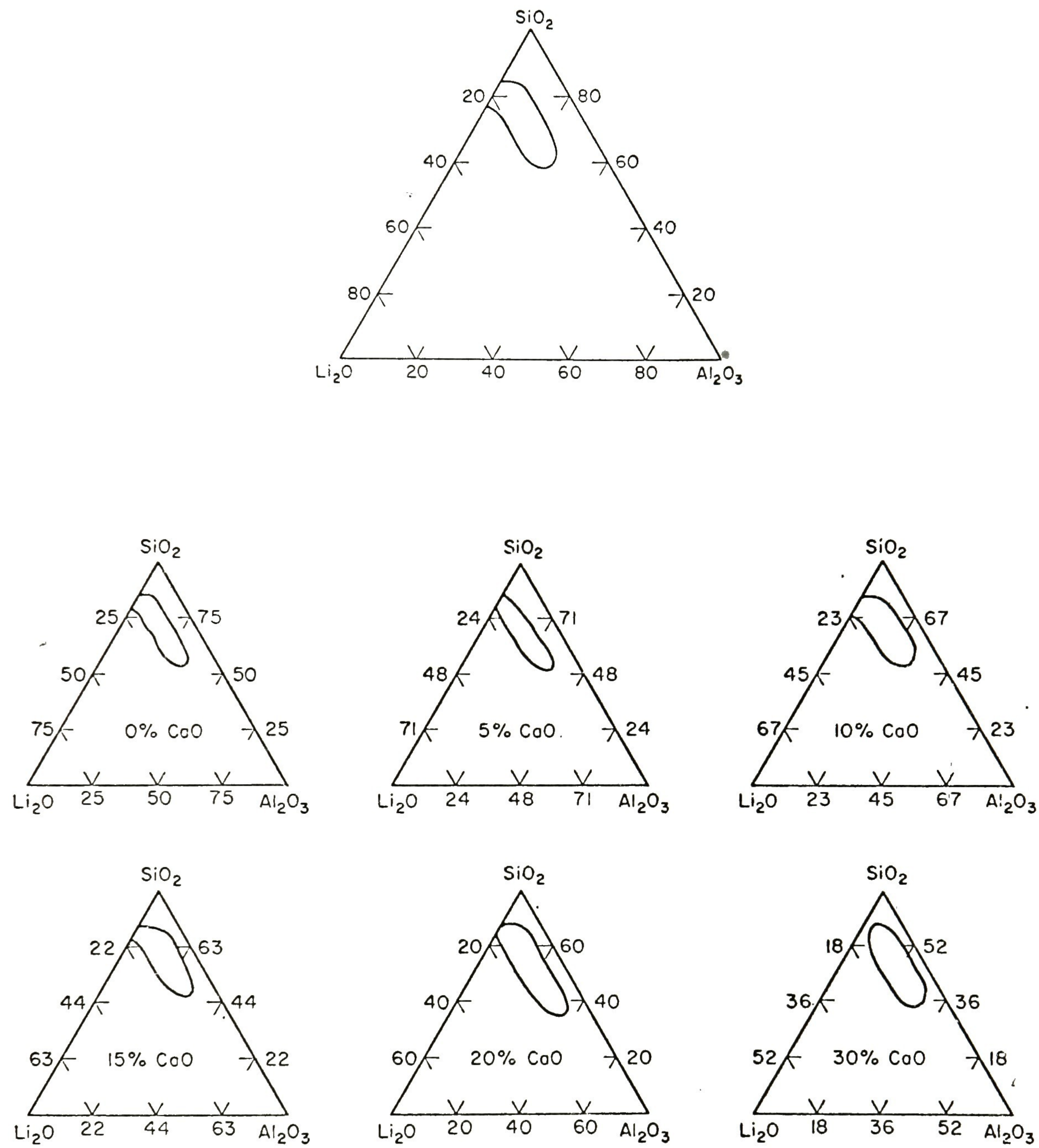


Figure 16. Systematic phase diagram used by Rauch, Common, and Blau to plot changes in fourth oxide.

helpful as a guide in respect to glazes utilizing these four oxides, but when used as a glaze on ceramics much can happen to alter these findings.

A suggested systematic procedure for developing thermal glazes

By comparing the percentage tables for my glaze tests with those utilized in the research article just discussed, one can see why my results do not lend themselves to graphic illustration very easily. This should point out the need for controlling the variables in such a way that meaningful analysis can result.

The central concern is to develop glazes that fit the bodies in such a way that the body is under compression from the glaze. This means the glaze needs to have a little lower coefficient of expansion than the body. We have seen that not just any ratio or quantity of a given ratio of lithia-alumina-silica will give low expansions, so it seems wise procedure to utilize Figure 7 and select a few compositions in the negative range which show negative expansion to begin with. The critical problem is to keep the lithia-alumina-silica ratios 'constant' toward each other, while a fourth oxide is 'varied' in constant intervals. This requires a great deal of mathematical juggling to achieve. Using barium, calcia, zinc, magnesia, boron, phosphorous, sodium, or potassium as fourth member oxides to be added, the lithia-alumina-silica ratio expansion can be altered toward a positive expansion which the bodies no doubt have. These tests should be run on both stoneware and porcelain thermal shock bodies because of the difference in body-glaze reactions and expansions. A concise example of this procedure from beginning to end is worked out in Appendix E. The results achieved should then be plotted on a phase diagram for every change in the fourth member. These diagrams then will indicate regions of contrast for the various qualities of interest.

A second, and easier approach, though less concrete and specific, is one which utilizes spodumene and petalite. The two minerals are, in themselves, a fixed ratio of lithia-alumina-silica which yield negative expansions. By making triaxial blends on the basis of the phase diagram, and by placing a lithia mineral at one corner of the triangle, one can test the effect of two oxides on the negative expansions of the fixed ratio contained in the lithia mineral. This makes possible the use of all the raw materials in the glaze pantry, and it is very easy to lay out and use. The problem here is that due to the impurities present, it becomes difficult to control and analyze the changes that occur. As seen in Appendix F the results can be recorded on a phase diagram just as for the previous approach.

CHAPTER IV

THE FIREPLACE

The fireplace as an influential, historical object

My orientation towards any object which is man-made grows out of some of the thoughts of several social philosophers, who suggest that to the degree that an object commands time, energy, and human involvement, to that degree it will control a segment of one's daily routine. In another vein, they suggest that while every object extends human potentials and functions, it also limits the nature of those potentials to its own inabilities and mechanisms. In this manner one's habits, ideas, attitudes, presumptions, indeed, one's whole life is controlled to a great extent by the universe of tools and objects which dominate our lives. What, then, can be said about an object or tool when it becomes obsolete?

In Western Europe and then in America, the fireplace was for half the year the dominant center of human activity. It provided light and heat in the cold, dark seasons, but only to a very limited, spatially defined area. All activities (cooking, eating, reading, mending, washing, socializing) were thus centered, and the effect of causing the family to stay close together is evident.

The innovations of candles, lanterns, electricity, cast iron, gas heat, and then central heating all served to release the family to other rooms and functions. Having no efficient value to us, the fireplace now remains for sentimental purposes which it performs with increasing awkwardness.

Initial impressions

As a typical member of a generation which is ignorant of some of the previous generation's 'authentic' sentimentality, I find little difficulty breaking with traditional expectations in order to seek a more genuinely appropriate solution for our time.

My initial ideas of a fireplace were more concerned with the firepot as a multi-sensory sculptural unit. This involved experimenting with the relationship between the qualities of clay, form, light, smoke, odor, sound, and heat as values in themselves.

When a fireplace is considered as a dynamic theater, one can have a great variety of solutions. The predominant feature of a fireplace, the flickering flame, has a great number of dynamic qualities in itself to which the firepot needs to act as a subordinant stage or window. While the flame does cause active interaction throughout the room because of its reflection, the view into the hearth still is more significant. The shape of the opening(s), the level of the opening(s), the number of openings, all serve to emphasize various segments of the total theater.

I am also enthused about exploring the visual qualities of smoke as it shifts and weaves until it dissipates. I am intrigued by an idea to consider how the smoke can be effectively released so its character is emphasized and worthy of notice and toleration.

By seeking to approach the fireplace with these ideas influencing my frame of mind, I feel I don't need to rely upon a learned, historical sensitivity through which to appreciate the qualities involved.

Practical criteria

While a fireplace can be nothing more than an open hearth in the center of a room, today's modern home tends to require a very clean, and efficient operation from a fireplace. This means that smoke can make or break a fireplace. The essential element that needs to be planned around for an efficient fireplace is 'sufficient draft'. Too 'much' draft causes the fire to burn too hot and too fast because the movement of fresh air into the hearth and up the chimney is too rapid. Too 'little' draft starves the fire of fresh air and smoking results; first, because the fire doesn't burn clean, and second, because the excess smoke can't be drawn up the chimney.

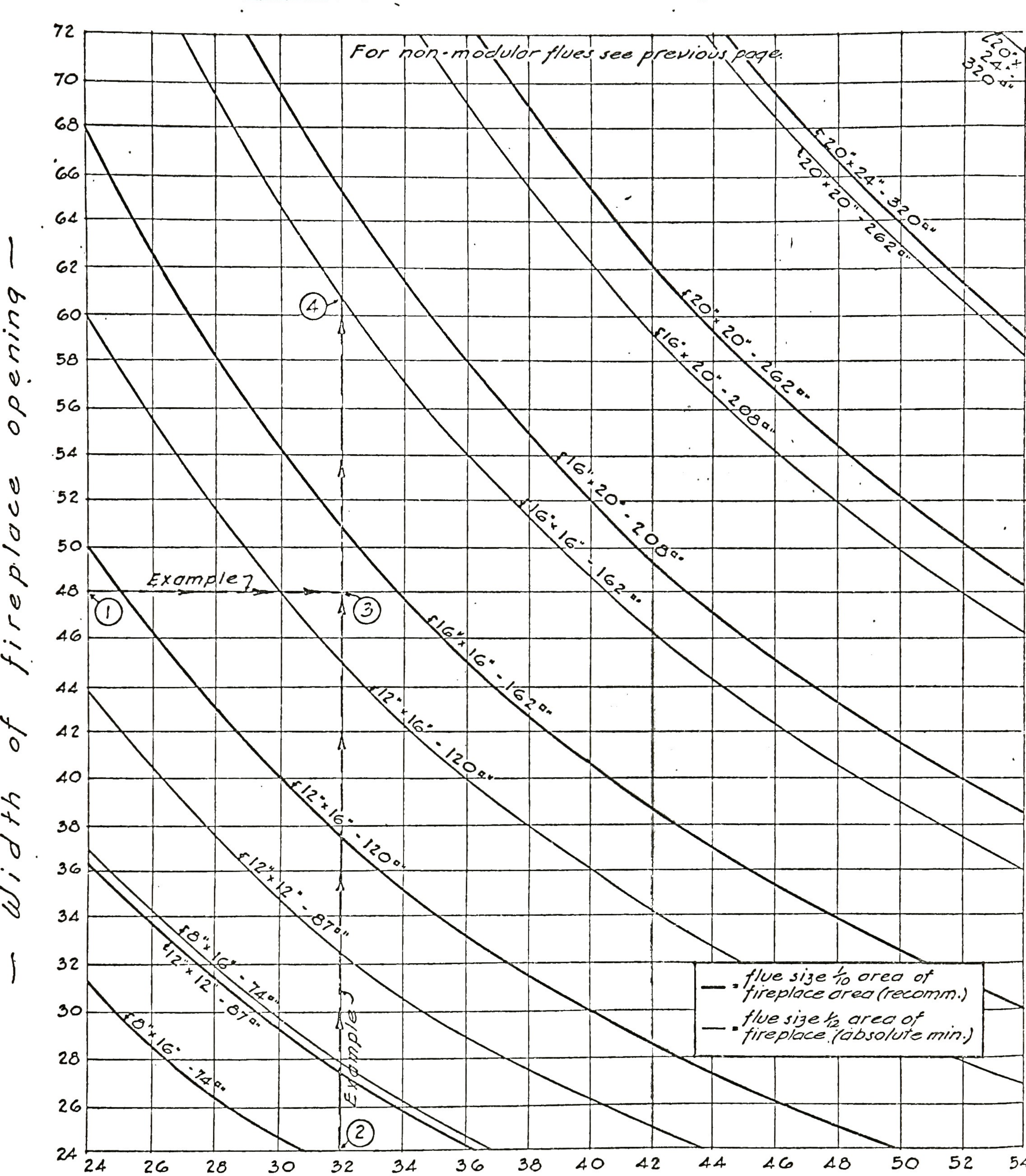
Technically, the height and diameter of the chimney dictates the total area that the opening(s) may have into the chamber. The more openings one has into the chamber, the wider the diameter and/or the higher the chimney must be. I found the general rule that the inside diameter of the chimney should be equal to one-tenth (1/10) of the combined area of all the openings in the hearth to be most generally followed. Figure 17 explains graphically this relationship.

Since the drawing of air up the chimney increases as the chamber and fire grow hotter, a damper is required to control the amount of air going up the chimney. Apparently the damper works best when it is a specific ratio and in a specific place in the chimney or hearth, although I found little in the way of a general rule. When the fire is out, the damper is required to prevent cold air from 'coming down' the chimney and 'into' the house.

Another problem in today's home is excessive heat radiation, which upsets modern thermostat measurement. To prevent this, one should consider making the hearth's walls thicker to cut down the amount of heat transfer

Figure 17. From Chas. G. Ramsey and Harold Reeve-Sleeper, _Architectural Graphic Standards_, (New York, 1956), p. 116.

MODULAR FLUE SIZES for FIREPLACES



Problem : Find proper modular flue size (@ 1/12 fireplace area) for fireplace 48" wide and 32" high.
Solution: ① Find 48" fireplace width at left of chart.
② Find 32" fireplace height at bottom of chart.
③ Follow width line across and height line up until they intersect.
④ Proper flue size will be nearest curve indicating 1/12 fireplace area above intersection (16"×16").
Modular flues only made in rectangular sizes. If round flue is desired for modular chimney, use non-modular round flue.
Chart based on net flue areas. If flue is less than 20' high it is advisable to use next larger flue size unless the intersection ③ falls well [illegible] area curve.

through the pot. If the thicker walls are also porous, heat conduction is reduced further by the voids. Another solution is to build a lining inside from the same clay body, a refractory castable, or insulating cement.

The final general problem which affects the design of a firepot is the qualities of the clay itself. If good workability, wet strength, and a zero thermal coefficient of expansion are not inherent in the clay body, limitations in form and technique will be encountered. Any changes in the shape of the form, which is made of a clay which 'does' expand on heating, need to be done gradually because heat flows easiest along and through a continuous plane. An even flow permits an even rate of expansion throughout the form. Any sudden angles serve to break up heat-flow immediately and stress or cracks are created by very uneven expansions of adjacent planes.

Since heat flows at a different rate through thin sections (quickly) than it does through thick sections (slowly), any changes in thickness will need to be made gradually. Any 'sudden changes' in thickness, or any 'increase' in thickness as progress is made away from the concentration of heat, causes uneven expansions and stress. A situation where heat is being concentrated on a thick area which gradually becomes thinner as it moves away would be most desirable, I believe. This I say because the thick section would heat slowly and expand slowly, and the heat flow would dissipate as it moves away from the concentration of heat through the thicker areas to the thinner areas. This would permit the thinner sections to heat very slowly and to expand very little as a result, causing an even change throughout the structure.

In spite of this suggestion, a monolithic structure of any size usually fails, as heat, and thus expansion, is usually high where the fire is but grows less as progress is made away to the more remote areas. This uneven ratio of expansion can become very great with intense, sudden heat application.

The possible solutions to these problems are modular or random sectional constructions, which permit each section to expand according to the intensity of heat it is exposed to. Changes in thickness and angles become boundaries of sections, allowing uneven expansions to occur without structural stress.

The difficulty with these solutions is the sacrifice in potential forms in many cases, and a sacrifice in structural strength physically. Smoking and strength can become critical if joints aren't precisely planned and executed. My objection to this is that it is inconsistent with my initial reasons for working large and monolithically. In foreseeing the possibility of never getting a clay which has sufficiently low expansion, the only solution is to line the firepot with a castable refractory after it is fired, which would coincide with efforts to reduce heat radiation mentioned earlier. This would permit me to continue to explore with much freedom a variety of forms and techniques, which was my objective in the beginning, in spite of the thermal expansion coefficient of the clay body.

Design solutions

My first attempts to solve the actual designing of a free standing fireplace were with drawings and models, which I feel were a waste of time. To get the feel of a life-size object containing life-size energy is very difficult until it is placed in a room or courtyard. When I had this experience, my whole awareness changed. Table sculpture and functional pottery can be monumental, yet when working in this scale one need not consider environmental ratios to achieve this quality. Scale here is more a function of eating and serving. But to build a free standing object which interacts directly with architecture and the whole human being, requires a whole new consciousness.

Previous to this experience I designed firepots that proved to be more suitable as hibachis, or large incense burners than as potential full-scale fireplaces. Most of these models were an effort to extent the pot from floor to ceiling by adding a pedestal and a chimney as a part of the form. This, I thought, would serve to integrate the chimney into the whole instead of merely being added on as an after-thought. While I struggled with this problem throughout my work, I don't think I'm any closer to a solution than when I started (Figure 18-20).

While I still feel excited about pursuing multiple openings for visual stage and frame effects, I never really tried any except in models. Designing openings really became a problem when I began making full scale firepots. Here, construction technique and overall form tended to cause several of my solutions to become after-thoughts. These solutions, like those I tried in my models, are an effort to exhibit the plastic qualities of clay. Except in one case, these efforts failed because the clay had to be rigid enough to support the pot when the openings were made. Plasticity was not a natural characteristic of the clay at this point, and most of the openings reveal the state of rigidity. I also never ceased to be bothered by the black void of the opening until I finally built a fire inside and saw

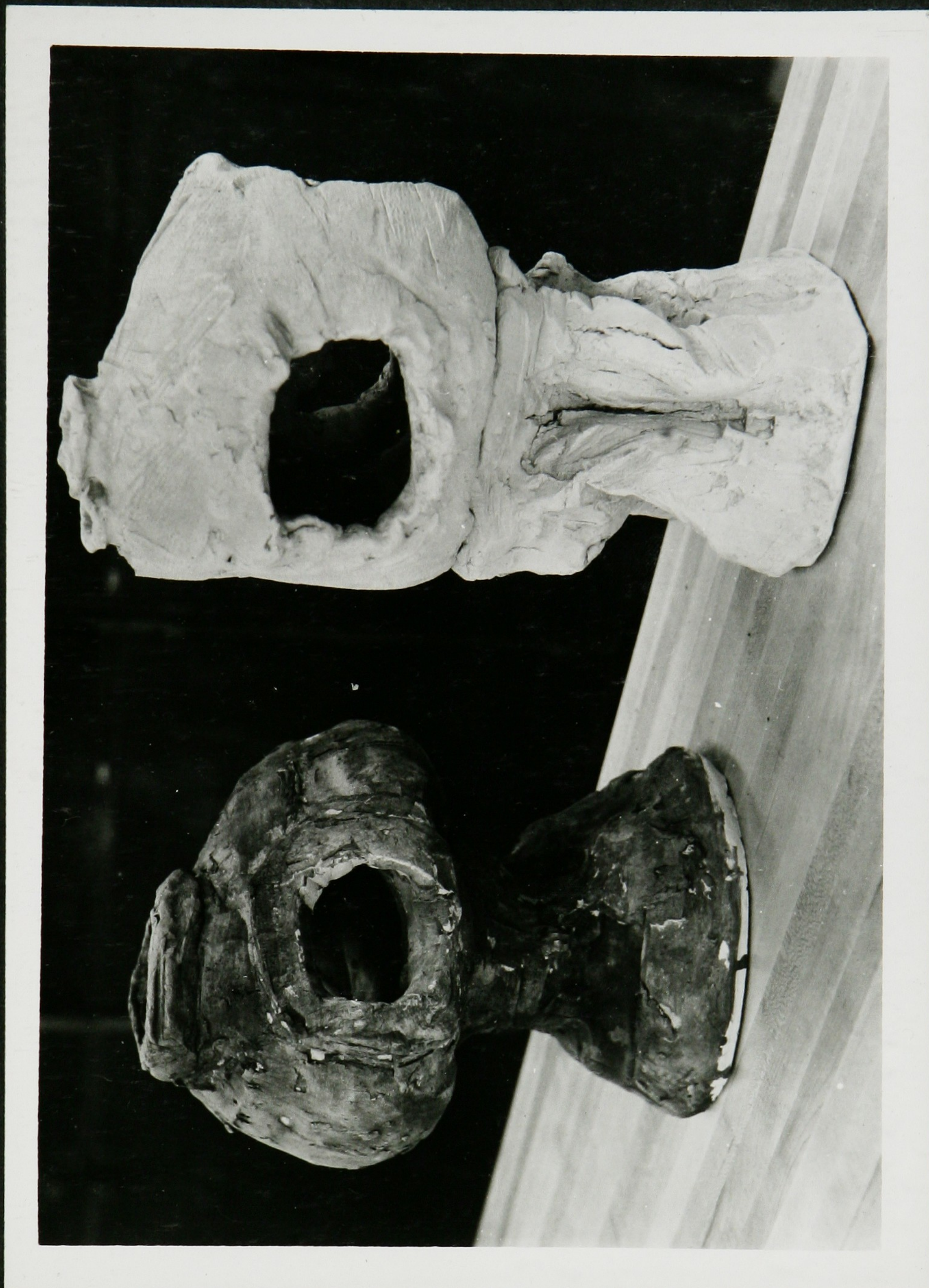


Figure 18. Two early, small models exploring multiple openings and pedestal problems.

Figure 19. Model unsuccessfully exploring use of base, chamber, and chimney as integral unit. It also attempted window effort for opening.

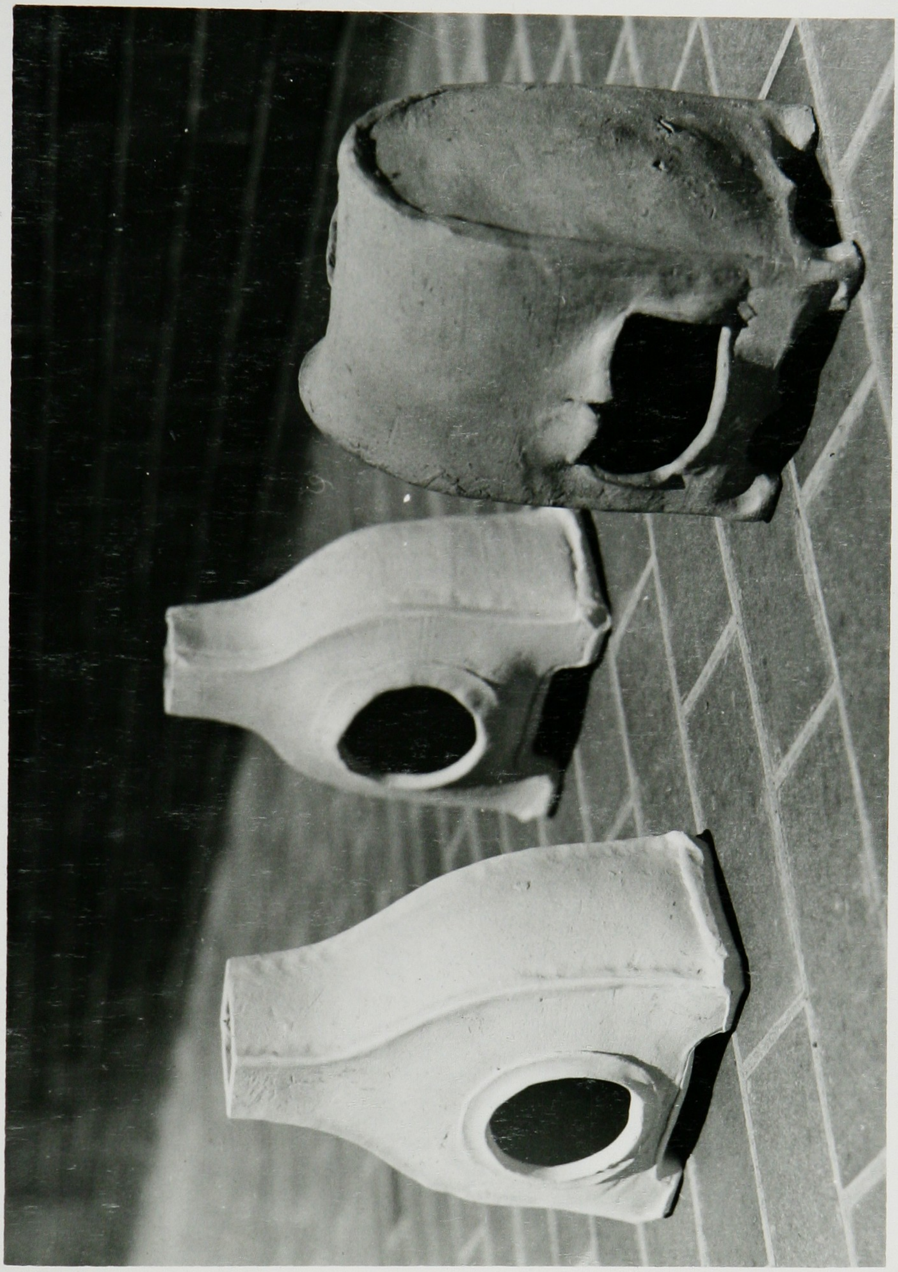


Figure 20. Three small models which would require a very rigid clay and other tools to build. Plastic quality of mouths would no doubt be lost. Larger form would be difficult to make.

Figure 21. Four foot high, coil built. Dried without cracks but many resulted in firing due, perhaps, to lack of thorough drying. Quality of opening is bothersome.

Figure 22 and 23. Most successful unit. Clay base and chamber separated by angle iron base. Iron support is too high and needs to be shortened. Piece has concave bottom which cracked during drying, but no cracks resulted in firing. It failed to stand up under intense heat, however, like the others. Chimney is still unsolved.

Figure 23. Another view.

what was necessary to think about when considering this (Figure 19).

The examples of Figure 20 failed because they either imitate designs more suitable for execution in another material, or because I lacked the equipment I would need to build several of the slab ideas I liked. I began building full size pots with very wet, large coils thumbed together and I became intrigued with the form which developed so naturally. The two variations that I felt were most successful encouraged other efforts, but as yet I have failed to control the technique enough to be satisfied with the results I have gotten. My initial reason was a concern to consciously overcome my very 'tight' approach to clay. Using clay as wet as I have has permitted me to play with it more, and to ignore a tendency to try and dominate it. I feel that the wet clay revealed its plastic character in spite of what I did (Figure 21-22).

The second reason is that I think I can avoid stresses and cracking if the clay is used wet. A 'stiffening' clay has a tendency to break or to build in stresses which later cause failure when drying and firing occur. Wet clay, by its very nature of being plastic, will bend and stretch without stressing itself. When a form is assumed which coincides with the properties of limp, plastic clay, construction cracks are less likely to occur.

In any case, drying the piece is a problem. I had some success in avoiding drying cracks when several layers of wax paper and ordinary paper were placed under the pot. Wrapping the top with plastic when the piece was finished, and leaving the plastic loose at the bottom so it dried out first helped avoid cracking of the bottom. Firing cracks were reduced when the pieces were thoroughly dried out in the hot boxes.

The flat-bottomed pieces were fired with success when left on a piece of plywood as large as the base of the pot. In loading the kiln, kiln shelves were first placed three or four inches off the bottom of the kiln. On top of these were placed groups of ceramic rollers so they would roll to the center of the circle; each group directly under the outside circumference of the firepot. On top of each group was placed a small piece of broken kiln shelf which was clean on its underside of all glaze. The firepot then was placed in the kiln so it rested on this circle of shelves, which, as firing proceeded, allowed the pot to shrink into the center by rolling with it. All horizontal surfaces needed to be kiln washed because when the plywood burns out, its ashes caused a glaze to be formed (Figure 24).

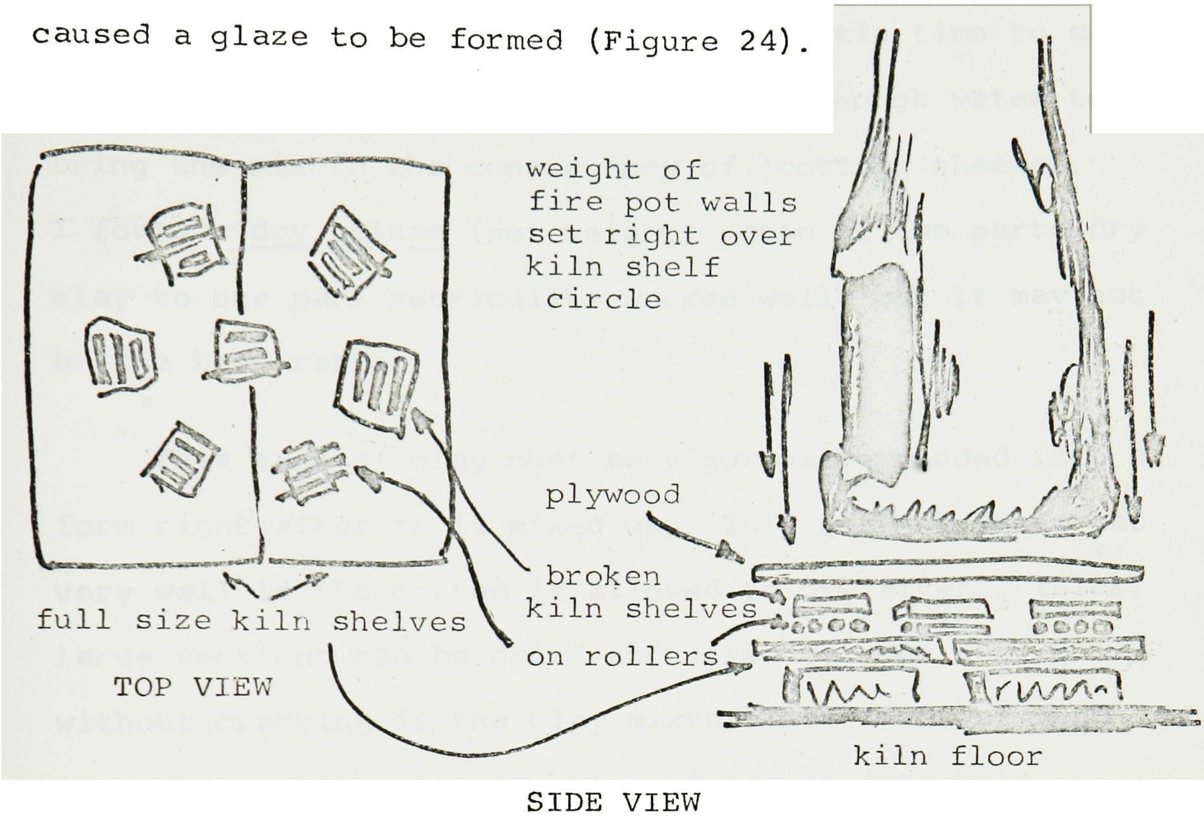


Figure 24. How the fire pots were fired in the kiln.

One fireplace with a concave bottom was fired successfully on a mound of loose silica sand, but wasn't as large nor as thick-walled (as heavy) as the others (Figures 22-23).

Vermiculite and thermal endurance

The technique of pounding a vermiculite-stoneware clay into the inside of a form was unsatisfactory because I didn't give enough thought to its totality as a design (Figure 25). It is very quick and easy to make firepots in this way, but it takes a little time to mix the dry clay-vermiculite mix with just enough water to bring the mix to the consistency of 'cottage cheese'. I found a dry volume (not weight) ratio of two parts dry clay to one part vermiculite worked well, but it may not be the best ratio.

This type of clay must be vigorously pounded into a form right after it is mixed up. This mixture dries out very well if the bottom is allowed to dry first. Thick, large sections can be dried and fired to cone 5 or 9 without cracking if the clay mixture isn't so wet that it packs together too tightly. Research into this approach has caused me to believe that diatomite is a much better choice than vermiculite.[12]

Conclusions

I regret having spent so much time making miniature models and not having made full size pieces which I could have not expected to save, but rather to destroy when their value as a learning device was appreciated and terminated.

---

[12] G. R. Eusner and J. T. Shapland, "Block Insulation for Stoves and Bustle Pipes," American Ceramic Society Bulletin, Vol. XL, (July, 1961), pp. 439-444.

I believe my time could have been better spent, and I could have gotten further once I did develop a body for thermal use. I also regret that I didn't get a chance to build a firepot in a whiteware body, but I still look forward to that. In any case I can only say that I have just scratched the surface in regard to firepot design potential. It has been a very frustrating task to work small because the whole object of the thesis was to work larger in spite of inevitable failure. I am glad that I attempted this whole problem at R.I.T. or I may not have gotten as far as I have in as little time.

Figure 25. Vermiculite - FSA body pounded into form. Meant to have pedestal of angle iron on large base pictured in Figure 21. Opening and form are not successful.

APPENDIX A

Tables of Porcelain Bodies Tested

Abbreviations Used

Ys	-	Yes (it is thixotropic)
G	-	Gray
Y	-	Yellow
W	-	White
C	-	Cream
T	-	Toast
P	-	Pink
O	-	Orange
B	-	Burnt
G	-	Golden
P	-	Pale
O	-	Off
S	-	Speckled
D	-	Dark
Bg	-	Bloating
Tr	-	Trace
F	-	a few
M	-	Many
O.K.	-	Endures 1000° F. Shock Test

SERIES: RL-Porcelain @ cone 9

	1	2	3	4	a	b	c	5	6	a	b	c	7	8	9	10	11	12	13	14	15	16	17	18
Total Clay Content	50	50	50	50	50	50	50	50	50	50	50	50	50	50	60	63	60	60	60	60	60	75	60	60
Flint	18	18	8	8	8	8	8								8									
Custar Spar	20			5	5	5	5								5									
Bainbridge Spar	5																							
Nepheline Spar	5			5	5	5	5	5	5	5	5	5			5	5	5	5	5	5	5	5	5	5
Dolomite	2	2	2	2	2			2	2	2			2	2	2									
Whiting						2					2					2								
Bone Ash																	5	5	5	5			5	5
Petalite		30	40	30	30	30	30	38	43	43	43	43	48	48										
Spodumene															20	30	30	30						
Lepidolite																								
Amblygonite																			30	20	20	20	23	26
Kyanite 100 Mesh																								
Kyanite 325 Mesh																								
Mullite 35 Mesh																								
Mullite 100 Mesh																								
Extra Fine Quartz																								
Thixotropic	Ys	Ys	Ys	Ys	Ys	Ys	Ys	Ys	Ys	Ys	Ys	Ys	Ys	Ys										
Color	G	GY	YG	G	G	G	G	pG	oW	Y	oW	W		CW	Bf	W	pO	O^{sp}	C	C	pO	pO	C	C
Total % Shrinkage	15	10	8	14	14	15	14	14	16	15	15	15	8	9	14	10	10	10		11	14	12	13	13
% Absorption	0	8	13	0	0	0	0	0	0	0	0	$1\frac{1}{2}$	12	12	1	13	4	8	$3\frac{1}{4}$	$2\frac{1}{2}$	1	7	$2\frac{1}{2}$	$1\frac{1}{2}$
Drying Cracks		tr	m		1	1	tr	tr	tr		tr	m	tr	tr	3		m	tr		2	m	m		
Firing Cracks		3	m						2		tr	tr	1		tr		m		Bg			m	Bg	Bg
Thermal Endurance	–	ok	ok	–	–	–	–	–	ok	–	ok	–	ok	ok	–	?	–	–	–	ok	–	–	–	–

SERIES: RL-Porcelain @ cone 9

SERIES:	19	20	21	22	23	24	25	26	2	27	28	29	30	31	32	33	34	35	36
Total Clay Content	60	60	60	60	60	60	60	60		60	60	60	60	60	60	60	60	60	60
Flint																			
Custar Spar																			
Bainbridge Spar																			
Nepheline Spar																			
Dolomite																			
Whiting																			
Bone Ash																			
Petalite																			
Spodumene	20	25	30	10	15	20	15	10									20	25	20
Lepidolite										30	35	25	30	25	25	20			
Amblygonite	5	5	5	10	10	10	15	20				5	5	10	10	15	15	15	20
Kyanite 100 Mesh																			
Kyanite 325 Mesh																			
Mullite 35 Mesh																			
Mullite 100 Mesh																			
Extra Fine Quartz																			
Thixotropic																			
Color	CW	pO	YC	OW	CW	C	O	O		GC	pBG	BG	BG	T	T	GT	gT	gT	dgT
Total % Shrinkage	13	11	11	12	12	18	14	14		14	12	10	10	11	9	11	12	12	12
% Absorption	8	11	$9\frac{1}{2}$	$7\frac{1}{2}$	$7\frac{1}{4}$	8	$6\frac{1}{2}$	0		0	0	0	0	2	.9	$4\frac{1}{2}$	$2\frac{1}{2}$	$2\frac{1}{2}$	$2\frac{1}{2}$
Drying Cracks	m			m	f	m	m	2				f	f				1		
Firing Cracks	m	f	f	m						2	2	Bg	Bg	-	-	Bg	ok	ok	ok
Thermal Endurance	ok	-	ok	ok	ok	ok	ok	-		-	-	-	-	-	-	-	ok	ok	ok

SERIES: RL-29a-s Porcelain @ cone 9

	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s
Total Clay Content	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
Flint																			
Custar Spar																			
Bainbridge Spar																			
Nepheline Spar																			
Dolomite																			
Whiting																			
Bone Ash																			
Petalite																			
Spodumene																			
Lepidolite	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35
Amblygonite																			
Kyanite 100 Mesh	10	20	30													15			
Kyanite 325 Mesh				10	20	30											15		
Mullite 35 Mesh							10	20	30									15	
Mullite 100 Mesh										10	20	30							15
Extra Fine Quartz													10	20	30	15	15	15	15
Thixotropic																			
Color	W	TC	spT	pT	W	W	gW	spO	spC	pT	pT	pT	TG	TC	TG	W	W	W	G
Total % Shrinkage	13	9	9	13	11	9	14	10	10	12	11	14	11	13	13	12	11	10	11
% Absorption	2½	8	1½	0	1½	4½	?	4	7	.8	4	5	0	.8	.8	.8	.8	1½	1½
Drying Cracks	f					2						2	f		m				
Firing Cracks			f	f	f					f				f	f		f		
Thermal Endurance	-	-	-	-	-	-	-	ok	-	ok	-	ok	-	-	-	-	-	-	ok

SERIES: R1-33a-s Porcelain @ cone 9

	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	r	s
Total Clay Content	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
Flint																			
Custar Spar																			
Bainbridge Spar																			
Nepheline Spar																			
Dolomite																			
Whiting																			
Bone Ash																			
Petalite																			
Spodumene																			
Lepidolite	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Amblygonite	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Kyanite 100 Mesh	10	20	30													15			
Kyanite 325 Mesh				10	20	30											15		
Mullite 35 Mesh							10	20	30									15	
Mullite 100 Mesh										10	20	30							15
Extra Fine Quartz													10	20	30	15	15	15	15
Thixotropic																			
Color	pGT	spP	PW	pT	PO	pP	pP	sp OP	spP	pCT	pPO	pPC	pT	GW	G	CPO	GP	spG	GYT
Total % Shrinkage	10	10	8	10	8	9	11	9	7	10	10	12	11	11	13	9	10	10	10
% Absorption	5	8	9	5	8	9½	8	10	9	2½	5	7	2	2	1	1½	3	4	1½
Drying Cracks																			
Firing Cracks																			
Thermal Endurance	ok	-	-	ok	-	-	ok	ok	ok	ok	ok	-	-	-	?	ok	-	ok	ok

SERIES: RL-Porcelain @ cone 9.

	37	a	38	a	b	c	39	a	b	c	40	a	41	a
Total Clay Content	40	40	40	40	40	40	40	40	40	40	40	40	40	40
Flint														
Custar Spar														
Bainbridge Spar														
Nepheline Spar													5	5
Dolomite														
Whiting														
Bone Ash														
Petalite	10	10	20	20	20	20	25	25	25	25	30	30	20	20
Spodumene														
Lepidolite	30	30	20	20	20	20	15	15	15	15	10	10	20	20
Amblygonite														
Kyanite 100 Mesh														
Kyanite 325 Mesh														
Mullite 35 Mesh						20				20				
Mullite 100 Mesh		15		15	20			15	20			15		15
Extra Fine Quartz	20	20	20	20			20	20	20		20	20	20	20
Thixotropic														
Color	tW	tW	tW	tW	W	W	tW	tW	W	W	tW	tW	tW	tW
Total % Shrinkage	12	11	14	11	8	7	12	12	7	8	14	12	14	13
% Absorption	0	0	0	1	1	1	0	0	1	1	1	1	0	0
Drying Cracks														
Firing Cracks	Bg												Bg	
Thermal Endurance	-	-	-	-	-	-	-	-	-	-	-	-	-	-

APPENDIX B

Tables of Stoneware Bodies Tested

SERIES: A.P. Green fireclay-Lithia Minerals @ cone 9

	S1	S2	S3	S4	S5	P1	P2	A1	A2	L1	L2	SA 1	SA 2	SA 3	SA 4	SA 5	LA 1	LA 2	LA 3
A.P. Green	90	80	75	70	90	75	70	90	80	80	70	90	85	80	80	75	75	70	70
F. - Stoneware Body																			
Petalite						25	30												
Spodumene	10	20	25	30	10							5	10	15	10	15			
Lepidolite										20	30						20	25	20
Amblygonite								10	20			5	5	5	10	10	5	5	10
Bone Ash					5														
Color	BT	OT	BO	pO	T	T	pT	cO	rO	sp dT	sp dGT	pT	S	S	pO	rO	dT	dGT	dT
Total % Shrinkage	12	8	7	5	10	12	11	11	10	12	10	13	9	8	9	8	10	10	7
% Absorption	4	9½	13	14	.7	4½	5	4	2	.4	.4	4½	6	9	9	7½	1	10	7
Drying Cracks	1																		
Firing Cracks	3								Bg		Bg						Bg	Bg	Bg
Thermal Endurance	ok	ok	ok	ok	-	-	-	-	-	-	-	-	-	?	?	ok	-	-	-

Bg= Bloating

p= pale, light
c= copper metal
d= dark
r= red
sp= speckle

B= Burnt
G= Gray
T= Toast
O= Orange
Sa= Salmon

SERIES: F-Stoneware--Lithia Minerals @ cone 9

	FS 1	FS 2	FS 3	FA 1	FA 2	FL 1	FL 2	FS A1	FS A2	FS A3	FS A4	FS A5	FS A6	FL A1	FL A2	FL A3
A.P. Green																
F. - Stoneware Body	90	80	70	90	80	80	70	85	80	75	70	80	75	75	70	70
Petalite																
Spodumene	10	20	30					10	15	20	25	10	15			
Lepidolite						20	30							20	25	20
Amblygonite				10	20			5	5	5	5	10	10	5	5	10
Bone Ash																
Color	TG	GT	pT	pGO	pO	GT	OT	T	T	OT	TO	TO	Sa	sp GT	sp T	sp GT
Total % Shrinkage	14	12	10	14	13	12	9	12	11	10	9	11	11	9	7	7
% Absorption	19¼	2½	8	2½	.8	2	0	2	2½	8¼	2	1½	4	1	7½	8
Drying Cracks	2			2		2										
Firing Cracks	2				Bg	Bg	Bg							Bg	Bg	Bg
Thermal Endurance	-	-	ok	-	-	-	-	-	-	ok	ok	-	?	-	-	-

Bg= Bloating

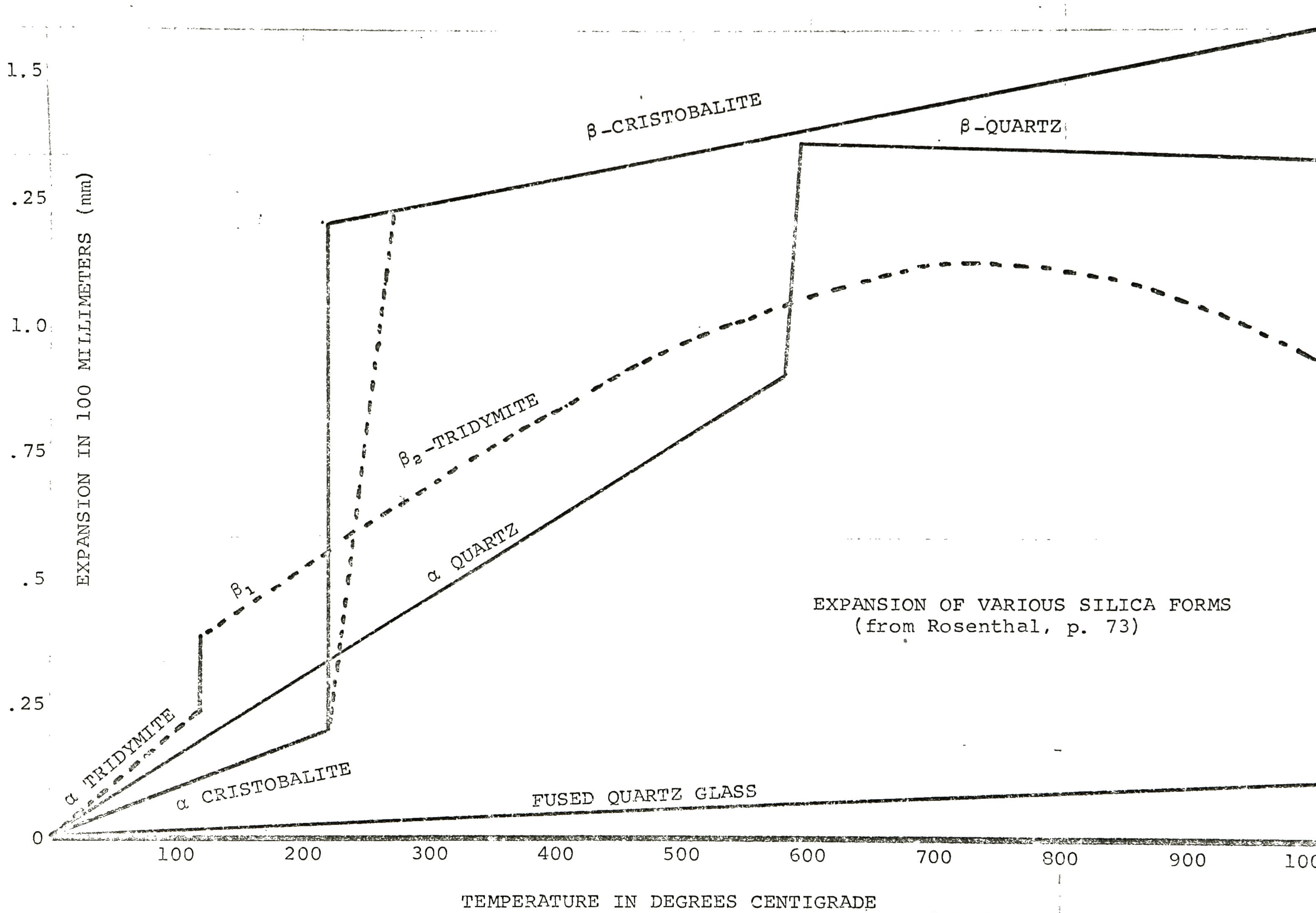
p= pale, light
d= dark
sp= speckled

G= Gray
T= Toast
O= Orange
Sa= Salmon

APPENDIX B-1

Percentage Analysis of Clays

and Clay Bodies



EXPANSION OF VARIOUS SILICA FORMS
(from Rosenthal, p. 73)

Procedure for Analyzing the Percentages of Oxides Present in a Clay Body.

Since each clay body is usually a composite of several clays and non-clay materials, it is necessary to determine how much of each oxide is contributed by a given amount of material. These are then totalled and adjusted to equal 100%. Since lithia, alumina, and silica are of primary interest, other oxides are neglected.

Body RL-35

EPK	=	40 parts
Tenn #5	=	20 parts
Spod.	=	25 parts
Amblyg.	=	15 parts

Body - FSA-4

XX Sagger	=	10 parts
AP Green Fireclay	=	25 parts
Tenn. #5	=	30 parts
Goldart	=	5 parts
Spod.	=	25 parts
Amblyg.	=	5 parts

RL-35 procedure

amt.	times	% (Al_2O_3	% SiO_2,	% Li_2O) =	% (Al_2O_3,	% SiO_2,	% Li_2O) supplied
EPK:40	x	(38	46	) =	(15.2	18.4	)
Tenn #5:20	x	(30	53	) =	(6.0	10.6	)
Spod:25	x	(28	63	7) =	(7.0	15.7	1.75)
Amblyg:15	x	(34		8) =	(5.1		1.2)
					33.3%	44.7%	2.95% = 81%

Most of what would total 100% is water lost in firing so these totals are adjusted so the three materials totalled 100%.

(33.3% Al_2O_3, 44.7% SiO_2, 2.95% Li_2O) ÷ 81% = (41% Al_2O_3,
55% SiO_2,
3.64% Li_2O) = 100%

Procedure for Analyzing the Percentages of Oxides Present in a Clay Body.

mat'l:amt.	x	% (Al_2O_3	% SiO_2	% Li_2O)		% (Al_2O_3,	% SiO_2	% Li_2O) supplied
XX Sagger:10	x	(29	51	0)	=	(2.9	5.7	0)
AP Green:25	x	(28	58	0)	=	(5.75	14.5	0)
Tenn #5:30	x	(30	53	0)	=	(10.0	15.9	0)
Goldart:5	x	(28	57	0)	=	(1.4	2.85	0)
Spod:25	x	(28	63	7)	=	(7.0	15.7	1.75)
Amblyg:5	x	(34	0	8)	=	(1.7	0	.4)
						(28.75,	54.65,	2.15%) = 85.5%

adjusting to 100% fired body

(28.75% Al_2O_3, 54.65% SiO_2, 2.15% Li_2O) ÷ 85.5% =

(33.4% Al_2O_3, 63.5% SiO_2, 2.5% Li_2O) = 100%

Chemical Analysis of A. P. Green Fireclay

SiO_2	55.0 - 58.0%
Al_2O_3	37.0 - 40.0%
Fe_2O_3	1.0 - 2.6%
CaO	.2 - .8%
MgO	.1 - .6%
TiO_2	1.0 - 2.0%
Alkalis	.5 - 1.5%

Edgar Plastic Kaolin Analysis

SiO_2	38.71%
Al_2O_3	45.91%
Fe_2O_3	.42%
TiO_2	.34%
CaO	.09%
MgO	.12%
Na_2O	.04%
K_2O	.22%
Ignition loss	14.15%

NAME Shipping Point *	GEM Gleason	JACKSON Gleason	KY-SPECIAL Mayfield	K-T IVORY Mayfield	M&D Sledge	KY#12 Mayfield	KY#40 Mayfield	L-I Gleason	MARTIN#5 Whitlock	OLD MINE#4 Mayfield
Particle Size, % 0.5	70	68	44	45	76	44	32	25	15	51
% Water of Plasticity	40	40	49	38	40	48	46	34	35	41
Dry M.O.R. **psi	880	750	850	560	>1400	770	680	700	570	720
% Linear Dry Shrinkage	5.4	5.3	6.2	5.2	6.1	6.3	5.6	5.5	5.1	5.3
% Total Shr. - Cone 5	14	13	16	12	15	14	14	10	11	14
% Total Shr. - Cone 12	17	17	19	15	16	18	17	13	14	17
% Absorption - Cone 5	10	11	14	13	0	13	15	12	10	9
% Absorption - Cone 12	0	1	2	5	0	4	4	2	1	1
Fired Color - Cone 12 ***	lt gry wh	gry wh	Lt. crm wh	iv	dk iv	lt gry wh	lt crm wh	lt crm	gry wh	lt gry wh
P.C.E.	32	32½	32	31	31	32	32	29	31½	32
SiO_2	54.9%	54.4%	48.8%	59.0%	57.1%	51.3%	53.9%	64.8%	59.4%	52.1%
Al_2O_3	29.8	30.1	29.0	25.2	27.8	28.0	26.3	20.9	25.9	31.2
TiO_2	1.6	1.6	1.5	2.5	1.3	1.7	1.5	1.2	1.4	1.6
Fe_2O_3	1.0	0.9	0.9	0.7	2.3	0.9	1.0	1.0	0.8	0.8
CaO	0.4	0.4	0.4	0.3	0.6	0.4	0.3	0.4	0.2	0.4
MgO	0.3	0.3	0.4	0.4	0.2	0.3	0.3	0.5	0.3	0.3
K_2O	0.4	0.3	1.0	0.5	0.5	1.0	1.2	1.6	1.9	1.0
Na_2O	0.1	0.1	0.2	0.3	0.3	0.2	0.5	0.2	0.4	0.3
L.O.I.	11.6	11.9	17.8	11.1	9.8	16.3	15.0	9.5	9.8	12.4

NAME Shipping Point *	TENN#5 Whitlock	TENN#9 Gleason	TENN#1 SGP Whitlock	TENN#10 Gleason	BENPINK Mayfield	DK WAD Whitlock	LT WAD Whitlock	XX SAGGER Gleason	KY#5 BOND Mayfield	KY#6 BOND Mayfield
Particle Size,%<0.5u	38	54	60	53	52	23	25	43	52	38
% Water of Plasticity	38	36	39	34	38	34	29	33	35	29
Dry M.O.R. ** psi	640	490	520	440	560	460	340	400	550	460
% Linear Dry Shrinkage	4.3	3.6	4.2	3.6	5.0	5.9	5.0	3.9	5.0	4.5
% Total Shr. - Cone 5	14	11	12	12	12	10	9	11	12	9
% Total Shr. - Cone 12	15	15	16	15	16	12	11	14	15	11
% Absorption - Cone 5	7	14	11	9	10	15	13	12	10	12
% Absorption - Cone 12	2	4	3	2	2	9	8	4	4	7
Fired Color - Cone 12***	gry wh	lt crm wh	wh	lt gry wh	gry crm	crm gry	crm gry	lt crm wh	crm wh	crm wh
P.C.E.	32	33	32-32½	32½-33	32	29-31	29-31	32½	31½	29-31
SiO_2	53.3%	51.8%	50.6%	50.4%	54.2%	62.6%	66.4%	56.7%	57.5%	63.8%
Al_2O_3	30.1	30.6	32.7	33.2	31.1	22.7	21.7	29.2	27.5	23.6
TiO_2	1.4	2.0	1.5	1.6	1.1	1.2	1.3	1.7	2.1	2.1
Fe_2O_3	1.0	0.8	0.8	0.9	1.7	1.1	1.4	0.7	0.7	0.8
CaO	0.3	0.6	0.3	0.3	0.1	tr	0.3	0.5	0.3	0.3
MgO	0.2	0.5	0.1	0.3	0.2	none	0.3	0.3	0.3	0.3
K_2O	1.5	0.8	0.9	0.7	0.9	1.0	0.7	0.9	1.1	0.7
Na_2O	0.8	0.3	0.5	0.5	0.6	0.3	0.3	0.3	0.4	0.3
L.O.I.	11.4	12.6	12.5	12.1	10.2	11.2	7.7	9.9	10.2	8.2

- Franklin Adams, Inc., 2102 South El Camino Real, San Clemente, Calif.
- Trinity Ceramic Supply, Inc., 9016 Diplomacy Row, Dallas 35, Texas
- Hammill & Gillespie, Inc., 225 Broadway, New York 7, New York
- Mineral Ceramic Products, Inc., 8326 Salt Lake Avenue, Bell, California
- S. Paul Ward, Inc., 601 Mission Street, South Pasadena, California
- Westwood Ceramic Supply Company. 14400 Lomitas Ave., City of Industry, Calif.

KENTUCKY-TENNESSEE CLAY CO., INC.
MAYFIELD, KENTUCKY 42066
PHONE 247-3061 AREA 502

Quantativo Analyses of various clays

Name of Clay	SiO_2	Al_2O_3	Fe_2O_3	KNaO	TiO_2	CaO	MgO	L.(
Kingsley	45.13	38.45	.38	.36	1.56	.08	.16	13.
Monarch	45.24	38.57	.30	.36	1.45	.10	.17	13.
English China	47.83	38.92	.30	1.05	——	——	.77	11.
EPK	45.91	38.71	.42	.26	.34	.09	.12	14.
Putnam	47.02	37.87	.80	.44	.21	.08	.16	13.
XX Sagger	56.68	29.19	.72	1.20	1.65	.45	.32	9.
M & D	57.03	27.92	2.17	.85	1.31	.46	.30	9.
Old Mine # 4	51.92	31.78	.87	1.27	1.52	.21	.19	12.
Kentucky Special	49.64	29.33	.95	1.25	1.48	.29	.25	16.
Tennessee # 5	51.79	31.31	1.01	2.31	1.41	.26	.20	11.
Imperial	55.94	27.12	.89	.54	1.75	.22	.34	13.
Rex	58.25	27.79	.94	1.10	1.49	.30	.23	8.
Yankee	58.66	25.40	2.29	2.87	1.21	.13	.75	8.
Bandy Black	61.00	24.54	.99	2.05	1.29	.09	.12	9.
English	51.18	32.54	1.03	2.86	1.75	.56	.39	9.
Goldart *	57.32	28.50	1.23	1.18	1.98	.08	.22	9.
Jordan	67.19	20.23	1.73	2.23	1.18	.16	.52	6.
Calvert	57.72	23.84	5.73	2.42	1.17	.31	.83	8.
Albany	57.65	15.75	4.92	4.90	——	6.28	3.20	7.
Michigan	58.21	12.70	6.33	4.88	——	9.35	1.30	7.
Fireclay	58.10	23.10	2.41	1.56	1.79	——	——	13.
Bentonite	59.50	16.10	3.07	2.69	——	3.12	2.65	6.

* .24 Sulphur

TYPICAL DATA ON UNITED SIERRA FLORIDA, GEORGIA, SOUTH CAROLINA KAOLINS FOR CERAMICS

		PUTNAM CLAY Plastic Kaolin	PUTNAM S CLAY Plastic Kaolin	CULVER CLAY Georgia Kaolin	HILLMAN CLAY Georgia Kaolin	KINGSLEY CLAY Coarse Ga. Kaolin	LAYTON CLAY Plastic Ga. Kaolin	MONARCH CLAY Casting Ga. Kaolin	ROGERS CLAY Plastic Ga. Kaolin	SAMSON CLAY Plastic Ga. Kaolin	CARVER CLAY Plastic Ga. Kaolin	UC-25 CLAY Casting Ga. Kaolin	HAMILTON #1 S. C. Kaolin
CHEMICAL ANALYSIS	SiO_2	47.02	46.49	44.89	45.89	45.13	46.57	45.24	46.02	45.58	45.45	45.46	45.21
	Al_2O_3	37.87	37.04	38.49	37.55	38.45	37.09	38.57	36.89	37.80	38.26	38.05	37.75
	Fe_2O_3	0.80	0.45	0.43	0.51	0.38	0.65	0.30	1.13	0.73	0.36	0.59	1.01
	TiO_2	0.21	0.18	1.64	1.26	1.56	1.29	1.45	1.10	1.25	1.52	1.32	1.97
	CaO	0.08	0.43	0.09	0.19	0.08	0.25	0.10	0.31	0.21	0.47	0.17	0.08
	MgO	0.16	0.30	0.18	0.24	0.16	0.24	0.17	0.24	0.22	0.04	0.20	0.12
	Na_2O	0.24	0.24	0.29	0.27	0.28	0.30	0.26	0.31	0.28	0.11	0.27	0.19
	K_2O	0.20	0.84	0.06	0.17	0.08	0.11	0.10	0.23	0.16	0.21	0.14	0.18
	LOI	13.49	14.56	13.95	13.91	13.88	13.54	13.86	13.79	13.81	13.47	13.82	13.65
	TOTAL	100.07	100.53	100.02	99.99	100.00	100.04	100.05	100.02	100.04	99.89	100.02	100.16
PARTICLE SIZE IN MICRONS	% Minus 10	83.5	88.5	85.0	82.0	78.5	83.0	74.0	90.0	81.0	88.5	79.5	97.0
	% Minus 5	77.0	83.5	74.0	68.0	65.0	75.0	61.0	83.0	71.0	78.0	68.0	94.0
	% Minus 2	68.5	70.0	54.0	49.5	45.0	60.5	40.0	70.0	54.5	59.5	53.5	86.0
	% Minus 1	59.0	61.5	38.0	34.5	30.5	46.5	23.0	59.0	41.0	50.0	40.0	76.0
	% Minus 0.5	48.0	50.5	23.0	20.0	17.0	33.0	11.0	44.0	27.0	32.0	28.0	62.0
	% Minus 0.2	24.0	25.0	7.0	9.0	4.5	17.5	2.5	24.0	12.0	12.5	11.0	33.0
PHYSICAL PROPERTIES	Water Plasticity	41.5	37.5	32.0	35.0	34.5	36.0	33.5	38.0	36.0	39.5	35.5	38.5
	MOR Dry (psi)	500†	650†	225*	325**	150*	600**	80*	655**	475**	450*	500*	260*
	PCE (Cone)	35	35	33-34	33-34	34-35	33	34-35	34	34	34-35	34	33-34
	pH	5.1	6.0-6.2	4.6	5.0	4.8	4.75	4.1	5.9	5.1	7.6	4.8	4.1
ABSORPTION	C/1	9.8	9.6	22.4	16.9	19.6	13.4	21.0	7.7	7.1	17.9	10.6	16.0
	C/5	5.5	5.2	18.7	13.7	15.8	8.6	17.8	6.2	5.8	12.5	9.2	7.1
	C/9	1.9	1.6	10.1	7.5	8.3	5.8	9.7	2.6	4.2	7.6	6.1	2.0
TOTAL SHRINKAGE	C/1	12.3	12.6	5.0	8.4	5.2	9.0	5.5	14.4	11.9	5.2	9.7	13.0
	C/5	15.0	15.5	6.8	10.0	7.0	11.2	7.3	15.4	13.0	8.4	10.9	17.6
	C/9	16.7	16.9	11.4	13.7	11.8	13.0	12.3	16.7	13.9	12.1	12.4	20.4

* Cast Neat Clay
† Cast 1/2 Clay – 1/2 Flint
** Extruded Neat Clay
†† Dry Pressed Neat Clay with 10% Moisture

TYPICAL DATA ON UNITED SIERRA TENNESSEE BALL CLAYS FOR CERAMICS

		CENTURY CLAY	COLTON CLAY	IMPERIAL CLAY	NORMAN CLAY	REGAL CLAY	REGENT CLAY	REX CLAY	ROYAL CLAY	STERLING CLAY	STRATTON CLAY	VICTORIA CLAY	WELDON CLAY	WINTON CL
CHEMICAL ANALYSIS	SiO_2	52.58	58.82	55.94	53.32	56.71	56.65	58.25	55.80	55.37	60.19	57.17	52.01	53.43
	Al_2O_3	29.76	26.99	27.12	31.24	28.87	28.84	27.79	28.70	29.32	26.47	28.45	30.34	28.89
	Fe_2O_3	0.98	1.01	0.89	0.91	0.86	0.99	0.94	0.99	1.15	0.90	0.96	0.97	0.99
	TiO_2	1.64	1.40	1.75	1.99	1.65	1.59	1.49	1.59	1.85	1.63	1.69	1.64	1.63
	CaO	0.37	0.32	0.22	0.18	0.26	0.24	0.30	0.29	0.24	0.31	0.26	0.35	0.39
	MgO	0.27	0.22	0.34	0.19	0.16	0.21	0.23	0.29	0.23	0.23	0.20	0.17	0.41
	Na_2O	0.24	0.28	0.28	0.19	0.30	0.30	0.28	0.30	0.30	0.33	0.31	0.20	0.30
	K_2O	0.78	1.70	0.26	0.63	0.19	0.17	1.82	0.83	0.28	0.42	0.21	0.38	1.38
	LOI	13.39	9.23	13.30	11.41	11.02	11.10	8.87	11.29	11.32	9.59	10.78	13.85	12.70
	TOTAL	100.01	99.97	100.10	100.06	100.02	100.09	99.97	100.08	100.06	100.07	100.03	99.91	100.12
PARTICLE SIZE IN MICRONS	% Minus 10	93.0	77.0	91.0	87.3	82.0	91.0	82.0	88.0	96.5	81.0	88.0	97.5	86.0
	% Minus 5	87.0	66.5	88.0	82.0	78.0	84.0	71.0	79.5	93.5	75.0	82.0	94.5	76.0
	% Minus 2	74.0	52.0	79.0	72.5	72.5	77.5	55.0	66.5	85.0	67.0	75.0	85.0	58.0
	% Minus 1	62.0	41.0	67.0	64.0	61.0	68.0	42.0	55.5	74.0	59.5	65.5	73.5	44.5
	% Minus 0.5	47.0	27.5	51.0	53.5	47.0	54.0	30.0	42.0	58.5	45.5	52.0	58.0	30.0
	% Minus 0.2	26.0	12.0	28.0	33.5	26.0	29.5	15.0	21.0	33.5	29.5	29.5	34.5	13.5
PHYSICAL PROPERTIES	Water Plasticity	40.0	36.0	39.0	38.0	37.7	36.5	35.0	37.0	39.5	35.5	36.5	41.0	39.5
	MOR* Dry (psi)	875	460	950	900	675	825	400	650	900	725	800	1150	375
	PCE (Cone)	32-33	31-32	32-33	32-33	32-33	32-33	31-32	31-32	32-33	32-33	31-32	32-33	31-32
	pH	4.3	4.7	4.4	4.5	4.7	4.4	4.5	4.2	4.2	4.5	4.4	4.2	4.3
ABSORPTION	C/1	11.4	6.4	8.5	9.6	10.9	5.0	5.8	8.6	10.7	8.9	9.2	6.7	6.1
	C/5	9.0	4.0	7.4	8.6	10.0	4.2	4.6	5.6	6.2	7.8	7.8	4.8	3.2
	C/9	5.0	0.3	4.6	5.3	5.0	1.6	0.6	2.0	3.3	5.6	4.3	2.1	0.2
**TOTAL SHRINKAGE	C/1	9.6	7.6	8.2	7.8	8.0	13.4	7.6	8.9	9.0	6.8	7.8	14.0	9.6
	C/5	10.5	8.9	8.7	8.9	8.8	14.0	8.6	9.8	10.4	7.4	8.3	14.6	10.8
	C/9	11.8	10.2	9.9	9.7	10.0	15.2	9.8	11.0	11.4	8.5	9.7	16.2	11.2

* Cast, 1/2 Clay – 1/2 Flint.
** Dry Pressed Neat Clay with 10% Moisture.

APPENDIX C

Analysis of Lithia Minerals

Empirical Formulas for Various Lithia Minerals

	Amblygonite	Lepidolite	Spodumene	Petalite
Mole. Wt.	296	393	419	666
Li_2O	.900	.544	.958	.900
K_2O	.010	.390	.031	.020
Na_2O	.083	.065	.031	.026
CaO	.010		.008	.023
MgO			.031	.031
Al_2O_3	1.007	1.000	1.197	1.032
Fe_2O_3	.003	.002	.013	.004
SiO_2	.006	3.741	4.449	8.130
P_2O_5	1.051			
F_2	.223	.534		

Weight % of Oxides Found in Various Lithia Minerals

	% Amblygonite	% β-Eucryptite	% Lepidolite	% Spodumene	% Petalite
Li_2O	8.43	11.8	4.00	6.78	4.43
K_2O	.3		9.00	.69	.56
Na_2O	1.63	.11	1.00	.46	
CaO	.15	.26		.11	.05
MgO		.18		.13	
F	2.61		5.00		
Al_2O_3	34.42	39.8	25.00	28.42	17.30
Fe_2O_3	.15	.35	.08	.53	.04
Cr_2O_3					.004
P_2O_5	46.75				
MnO_2					.02
TiO_2		1.1			
SiO_2	.36	46.4	55.0	62.91	76.10
H_2O (Combined)	4.30			.28	

Sources:

Amblygonite: Ceramic Industry, Vol. LXXXII, (January, 1964), p. 189.

β-Eucryptite: Ceramic Industry, Vol. XCII, (January, 1969), p. 103.

Lepidolite: Ceramic Industry, Vol. LXXXII, (January, 1964), p. 132.

Spodumene: Ceramic Industry, Vol. LXXXII, (January, 1964), p. 164.

Petalite: Foote Mineral Technical Data Bulletin, No. 301.

Appendix D

Analysis of Glazes Tested

Empirical Formulas for Some Glazes Tested.

Series	Li_2O	CaO	BaO	Al_2O_3	P_2O_5	SiO_2
WA-7	.227	.742		.706	.268	2.123
WL-2	.109	.800		.515		2.048
WL-3b	.136	.776		.378		2.43
WL-6	.109	.800		.359		2.401
WS-3	.182	.800		.384		1.8
WS-6	.182	.800		.384		2.5
WS-8-1	.347	.639		.662	?	2.113
WP-2	.115	.870		.287		2.12
WP-6	.115	.870		.287		2.85
WP-2g	.234	.728		.578	?	2.83
BaA-3	.351		.603	.700	.414	2.546
BaA-4	.341		.603	.868	.414	2.776
BaL-3c	.306		.557	.666	?	3.29
BaL-3c-1	.144	.523	.267	.319	?	1.58
BaL-3c-2b	.144	.523	.267	.536	?	2.26
BaL-5a-5	.198	.447	.227	.362	.160	2.08
BaS-9	.421		.513	.761		4.152
BaS-2a/3c	.381		.567	.706	.178	3.438
BaS-5a	.112	.575	.300	.271		2.5
BaP-3b	.304		.689	.650	.216	3.682
BaP-3c	.342		.646	.677	.202	3.456
BaP-a/c	.220	.502	.225	.310	.180	1.560

Oxide present in quantities less than .1 are not included in these analyses. Phosphorous present in minimal amounts is indicated with question marks.

Percent Analysis of Some Glazes Tested

Series	Li_2O %	CaO %	BaO %	P_2O_5 %	Al_2O_3 %	SiO_2 %
WA-7	2.4	14.4		13.2	25.1	44.5
WL-2	1.36	20.2			23.1	54.7
WL-3b	1.67	22.5			15.9	60.5
WL-6	1.43	19.75			16.5	63
WS-3	2.78	22.7			19.9	54.5
WS-6	2.29	18.7			16.4	62.5
WS-8-1	4.3	14.8			27.5	53
WP-2	1.65	23.3			14.0	60.7
WP-6	1.36	19.3			11.6	68
WP-2g	2.52	15.8			21.05	60.1
Bal-5a-5	2.36	10	13.8	9.1	14.8	50
Bal-3c-1	2.17	13.1	20.3	?	16.3	47.6
Bal-3c-2b	1.65	10	15.7	?	20.8	52
BaS-5a	1.29	12.4	17.8		10.7	58
BaP-a/c	3	12.6	15.6	11.6	14.3	42.5
BaA-3	2.72		23.8	15.3	18.5	39.6
BaA-4	2.5		22.1	14.1	21.2	40
BaL-3c	2.53		23.6	?	18.9	55
BaS-2a/3c	2.86		21.3	6.35	18.1	51.2
BaP-3b	2.78		3.2	6.33	20.2	67.5
BaP-3c	2.49		24.0	6.95	16.7	50
BaS-9	3.2		18.8		18.5	59.6

% lithium:aluminum:silica ratio without 4th oxide

Series	4th Oxide:Ternary %		Ternary ratio adjusted to 100% Li_2O:	Al_2O_3:	SiO_2	Description of Glaze CZ	Sr	B	M	S	f
WS-8-1	15	85	5.05	32.2	62.5				X	X	
WP-2g	16	84	3.0	25.0	72.0				X	X	
BaS-9	19	81	3.95	22.8	73.5				X		
WS-6	19	81	2.83	20.2	77	X		X		X	
WL-6	19	81	1.72	20.4	78	X		X			X
WP-6	19	81	1.68	14.3	84		X	X		X	
WL-2	21	79	1.74	29.2	69	X			X		X
WL-3b	22	78	2.14	20.4	77.5	X		X			X
WS-3	23	77	3.6	25.8	71	X		X			X
BaL-3c	23	77	3.3	24.6	72		X		X	X	
WP-2	24	76	2.07	18.4	79.5	X		X			X

CZ = craze B = bright S = stiff glaze

Sr = shiver M = mat f = fluid glaze

To clarify the procedure followed in arriving at the tables shown here, I have given an example of how I did so for one of the glazes actually tested and included. Since I was not following a system which permitted meaningful analysis of the results, (too many oxides were changing at once) I feel no conclusions of definite value can be made. This was my fault. Instead I recommend following the procedures used in Appendix E because every step can lend itself to meaningful analysis of the results.

Original glaze recipe WP-2 conversion procedures.

Petalite 40 gr. ÷ 666 (mole wt. of petalite) = .06 (.9 Li_2O:.02 K_2O:.02 Na_2O:.023 CaO:.031 MgO:1.032 Al_2O_3:8.130 SiO_2)

the empirical formula of petalite.

Whiting 40 gr. ÷ 100 (mole wt. of Whiting) = .4 CaO

Ball clay 20 gr. ÷ 258 (mole wt. of ball clay) = .078 (Al_2O_3:2SiO_2)

Silica 20 gr. ÷ 60 (mole wt. of silica) = .333 SiO_2

Li_2O	K_2O	Na_2O	MgO	CaO	Al_2O_3	SiO_2	
.054	.001	.002	.001	.001	.064	.487	from petalite
				.4			from whiting
					.078	.156	from ball clay
						.333	from silica
.054	.001	.002	.001	.401	.132	.976	relative mole. formula.
		totals 459					
.115	.002	.004	.004	.870	.287	2.12	empirical formula

Empirical Formula (significant oxide quantities only) of WP-2 converted to percentages.

$$Li_2O \quad .115 \times 30 \text{ (mole wt. } Li_2O) = 3.45 \div 208.55 = .0165 \times 100\% = 1.65\% \ Li_2O$$

$$CaO \quad .870 \times 56 \text{ (mole wt. } CaO) = 48.8 \div 208.55 = .233 \times 100\% = 23.3\% \ CaO$$

$$Al_2O_3 \quad .287 \times 102 \text{ (mole wt. } Al_2O_3) = 29.3 \div 208.55 = .140 \times 100\% = 14.0\% \ Al_2O_3$$

$$SiO_2 \quad 2.12 \times 60 \text{ (mole wt. } SiO_2) = \underline{127.0} \div 208.55 = .607 \times 100\% = \underline{60.7\%} \ SiO_2$$

208.55

99.65% or approx. 100%

Conversion of percentages to CaO:ternary percentage ratio.

$100\% - 23\%$ CaO = 77% approx. ternary percent

$$Li_2O \quad 1.65\% \div 77\% = 2.07\% \ Li_2O$$

$$Al_2O_3 \quad 14.0\% \div 77\% = 18.4\% \ Al_2O_3$$

$$SiO_2 \quad 60.7\% \div 77\% = 79.5\% \ SiO_2$$

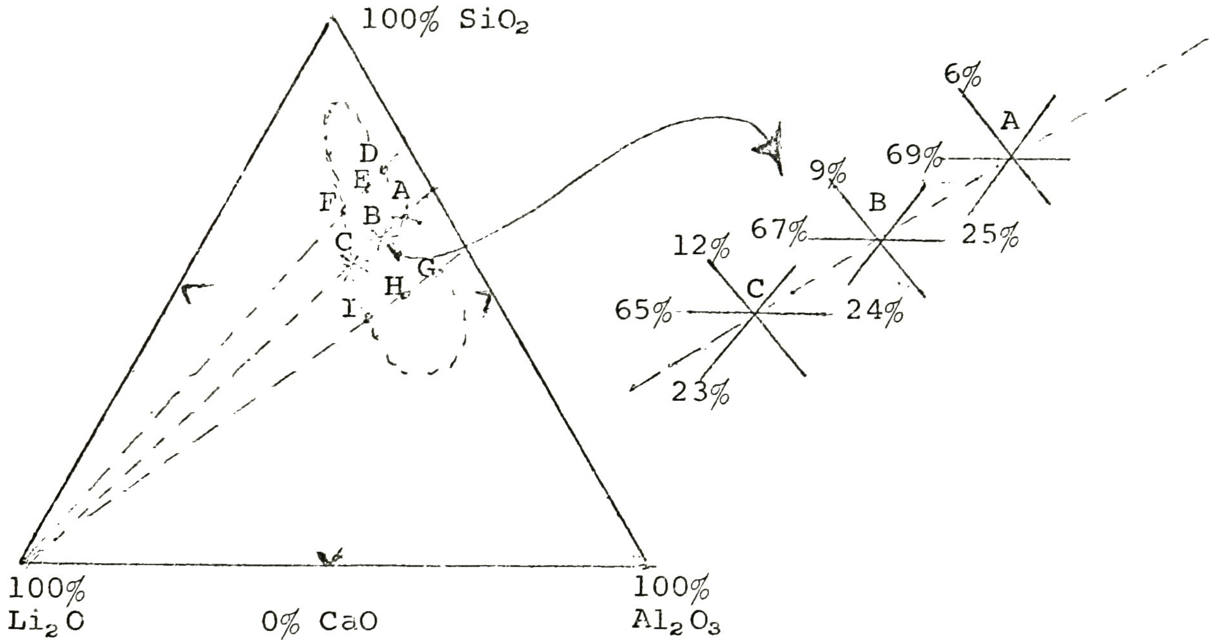
CaO:ternary ratio = 23%:77% (2.07% Li_2O, 18.4% Al_2O_3:79.5% SiO_2 = 100% of 77%)

APPENDIX E

The Ternary: Fourth Member Oxide System

of Glaze Computation and Analysis

Step 1. Select points at random within the area of negative expansion (Figure 7). In this case a line is drawn from the lithium apex through the area of negative expansion because it seems more important to vary the lithia and to keep the aluminum:silica ratio constant. A meaningful analysis would perhaps use all of the points A-I and more too, but this example will use only points A-C for illustration.

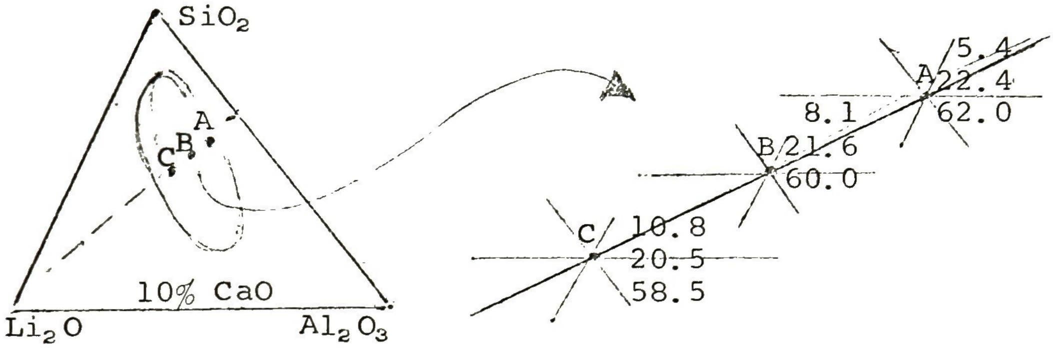


Point A = 6% Li_2O, 25% Al_2O_3, 69% SiO_2

Point B = 9% Li_2O, 24% Al_2O_3, 67% SiO_2

Point C = 12% Li_2O, 23% Al_2O_3, 65% SiO_2

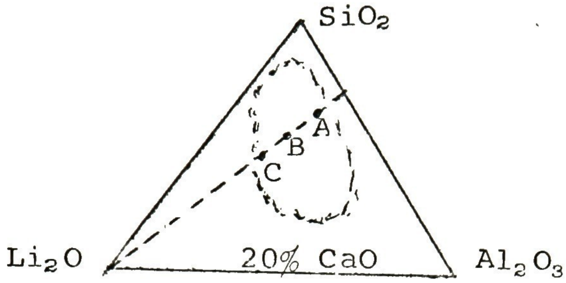
Step 2. The amount of increases of the fourth oxide to be added to the system are chosen, in this case, 10, 20, and 30% calcia are the fourth oxide quantities chosen. To keep the ternary ratio for points A-C constant, the following procedure is followed.

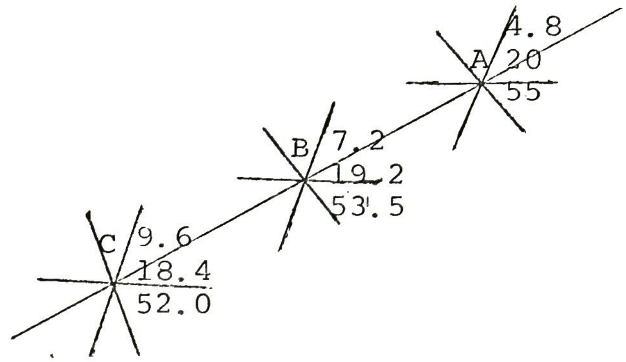


100% - 10% calcia = 90% ternary left

90% x point A	or	6%	Li_2O	=	5.4%	actual Li_2O
		25%	Al_2O_3	=	22.4%	actual Al_2O_3
		69%	SiO_2	=	62.0%	actual SiO_2
				=	90.0%	
90% x point B	or	9%	Li_2O	=	8.1%	actual Li_2O
		24%	Al_2O_3	=	21.6%	actual Al_2O_3
		67%	SiO_2	=	60.0%	actual SiO_2
				=	100.0%	
90% x point C	or	12%	Li_2O	=	10.8%	actual Li_2O
		23%	Al_2O_3	=	20.5%	actual Al_2O_3
		65%	SiO_2	=	58.5%	actual SiO_2
				=	100.0%	

(Step 2 - continued)



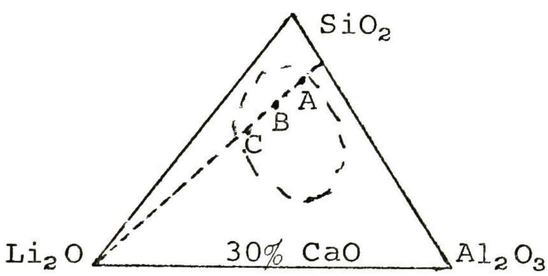


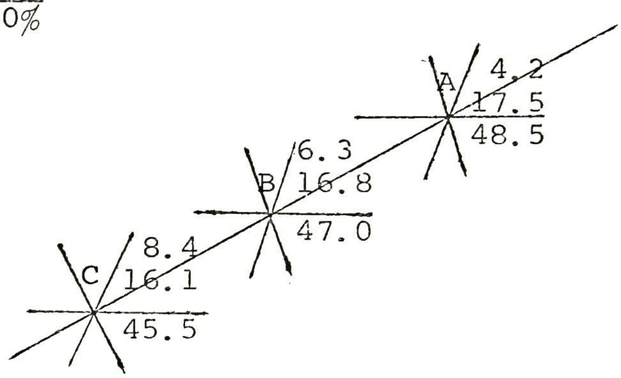
100% - 20% Calcia = 80% ternary

80% x pt. A or 6% Li_2O = 4.8%
or 25% Al_2O_3 = 20.0%
or 69% SiO_2 = 55.0%
79.8%

80% x pt. B or 9% Li_2O = 7.2%
24% Al_2O_3 = 19.2%
67% SiO_2 = 53.5%
79.9%

80% x pt. C or 12% Li_2O = 9.6%
23% Al_2O_3 = 18.4%
65% SiO_2 = 52.0%
80.0%





100% - 30% CaO = 70% ternary

70% x pt. A or 6% Li_2O = 4.2%
25% Al_2O_3 = 17.5%
69% SiO_2 = 48.5%
70.2%

70% x pt. B or 9% Li_2O = 6.3%
25% Al_2O_3 = 16.8%
69% SiO_2 = 47.0%
70.1%

70% x pt. C or 12% Li_2O = 8.4%
23% Al_2O_3 = 16.1%
65% SiO_2 = 45.5%
70.0%

STEP 3. The actual percentages of the four oxides are converted to a raw materials batch for actual testing.

10% CaO at pt A

CaO 10 %	÷ 56	(moles of CaO)	= .179	relative # moles CaO
Li_2O 5.4%	÷ 30	(moles of Li_2O)	= .180	relative # moles Li_2O
Al_2O_3 22.4%	÷ 102	(moles of Al_2O_3)	= .220	relative # moles Al_2O_3
SiO_2 62 %	÷ 60	(moles of SiO_2)	= 1.03	relative # moles SiO_2

Li_2O	CaO	Al_2O_3	SiO_2	
.180	.179	.220	1.470	Li_2CO_3
.180				.180 x 74 = 13.3 gr.
x	.179			Whiting
	.179			.179 x 100 = 17.9 gr.
	x	.220		Kaolin
		.220	.440	.220 x 258 = 57.0 gr.
		x	1.030	Flint
			1.030	1.03 x 60 = 61.5 gr.
			x	

10% CaO at pt B

CaO 10 %	÷ 56	(moles of CaO)	= .179	relative # moles CaO
Li_2O 8.1%	÷ 30	(moles of Li_2O)	= .270	relative # moles Li_2O
Al_2O_3 21.6%	÷ 102	(moles of Al_2O_3)	= .212	relative # moles Al_2O_3
SiO_2 60%	÷ 60	(moles of SiO_2)	= 1.00	relative # moles SiO_2

Li_2O	CaO	Al_2O_3	SiO_2	
.270	.179	.212	1.424	Li_2CO_3
.270				.27 x 74 = 20.0 gr.
	.179			Whiting
	.179			.179 x 100 = 17.9 gr.
	x	.212		Kaolin
		.212	.424	.212 x 258 = 54.5 gr.
		x	1.00	Flint
			1.00	1.0 x 60 = 60.0 gr.
			x	

10% CaO at pt C

CaO	.10%	÷	56 (moles of CaO)	=	.179	relative # moles CaO
Li_2O	10.8%	÷	30 (moles of Li_2O)	=	.360	relative # moles Li_2O
Al_2O_3	20.5%	÷	102 (moles of Al_2O_3)	=	.200	relative # moles Al_2O_3
SiO_2	58.5%	÷	60 (moles of SiO_2)	=	.975	relative # moles SiO_2

Li_2O	CaO	Al_2O_3	SiO_2					
.360	.179	.200	1.375	Li_2CO_3				
.360				.36 x	74	=	26.6	gr.
x	.179			Whiting				
	.179			.179 x	100	=	17.99	gr.
	x	.200		Kaolin				
		.200	.400	.2 x	258	=	51.5	gr.
		x	.975	Flint				
			.975	.975 x	60	=	58.5	gr.
			x					

20% CaO at pt A

CaO	20%	÷	56 (moles of CaO)	=	.357	relative # moles CaO
Li_2O	4.8%	÷	30 (moles of Li_2O)	=	.160	relative # moles Li_2O
Al_2O_3	20.0%	÷	102 (moles of Al_2O_3)	=	.196	relative # moles Al_2O_3
SiO_2	55 %	÷	60 (moles of SiO_2)	=	.920	relative # moles SiO_2

Li_2O	CaO	Al_2O_3	SiO_2					
.160	.357	.196	1.312	Li_2CO_3				
.160				.16 x	74	=	11.8	gr.
x	.357			Whiting				
	.357			.357 x	100	=	35.7	gr.
	x	.196		Kaolin				
		.196	.392	.196 x	258	=	50.5	gr.
		x	.920	Flint				
			.920	.920 x	60	=	55.0	gr.
			x					

20% CaO at pt B

CaO 20% ÷ 56 (moles of CaO) = .357 relative # moles CaO
Li_2O 7.2% ÷ 30 (moles of Li_2O) = .240 relative # moles Li_2O
Al_2O_3 19.2% ÷ 102 (moles of Al_2O_3) = .188 relative # moles Al_2O_3
SiO_2 53.5% ÷ 60 (moles of SiO_2) = .890 relative # moles SiO_2

Li_2O	CaO	Al_2O_3	SiO_2	
.240	.357	.188	1.266	Li_2CO_3
.240				.240 x 74 = 17.8 gr.
x	.357			Whiting
	.357			.357 x 100 = 35.7 gr.
	x	.188		Kaolin
		.188	.376	.188 x 258 = 48.5 gr.
		x	.890	Flint
			.890	.890 x 60 = 53.5 gr.
			x	

20% CaO at pt C

CaO 20% ÷ 56 (moles of CaO) = .357 relative # moles CaO
Li_2O 9.6% ÷ 30 (moles of Li_2O) = .320 relative # moles Li_2O
Al_2O_3 18.4% ÷ 102 (moles of Al_2O_3) = .180 relative # moles Al_2O_3
SiO_2 52% ÷ 60 (moles of SiO_2) = .870 relative # moles SiO_2

Li_2O	CaO	Al_2O_3	SiO_2	
.320	.357	.180	1.230	Li_2CO_3
.320				.320 x 74 = 23.7 gr.
x	.357			Whiting
	.357			.357 x 100 = 35.7 gr.
	x	.180		Kaolin
		.180	.360	.180 x 258 = 46.5 gr.
		x	.870	Flint
			.870	.870 x 60 = 52.0 gr.
			x	

30 % CaO at pt A

CaO 30% ÷ 56 (moles of CaO) = .535 relative # moles CaO
Li_2O 4.2% ÷ 30 (moles of Li_2O) = .140 relative # moles Li_2O
Al_2O_3 17.5% ÷ 102 (moles of Al_2O_3) = .171 relative # moles Al_2O_3
SiO_2 48.5% ÷ 60 (moles of SiO_2) = .810 relative # moles SiO_2

Li_2O	CaO	Al_2O_3	SiO_2	
.140	.535	.171	1.152	Li_2CO_3
.140				.140 x 74 = 10.4 gr.
x	.535			Whiting
	.535			.535 x 100 = 53.5 gr.
	x	.171		Kaolin
		.171	.342	.171 x 258 = 44.0 gr.
		x	.810	Flint
			.810	.810 x 60 = 48.5 gr.
			x	

30 % CaO at pt B

CaO 30 % ÷ 56 (moles of CaO) = .535 relative # moles CaO
Li_2O 6.3 % ÷ 30 (moles of Li_2O) = .210 relative # moles Li_2O
Al_2O_3 16.8% ÷ 102 (moles of Al_2O_3) = .165 relative # moles Al_2O_3
SiO_2 47.0% ÷ 60 (moles of SiO_2) = .780 relative # moles SiO_2

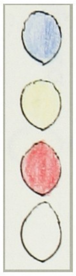
Li_2O	CaO	Al_2O_3	SiO_2	
.210	.535	.165	1.110	Li_2CO_3
.210				.210 x 74 = 15.5 gr.
x	.535			Whiting
	.535			.535 x 100 = 53.5 gr.
	x	.165		Kaolin
		.165	.330	.165 x 258 = 42.5 gr.
		x	.780	Flint
			.780	.780 x 60 = 57.0 gr.
			x	

30 % CaO at pt C

CaO	30 %	÷ 56	(moles of CaO)	=	.535 relative # moles CaO
Li_2O	8.4 %	÷ 30	(moles of Li_2O)	=	.280 relative # moles Li_2O
Al_2O_3	16.1%	÷ 102	(moles of Al_2O_3)	=	.158 relative # moles Al_2O_3
SiO_2	45.5%	÷ 60	(moles of SiO_2)	=	.760 relative # moles SiO_2

Li_2O	CaO	Al_2O_3	SiO_2						
.280	.535	.158	1.076	Li_2CO_3					
.280				.280	x	74	=	20.7	gr.
x	.535			Whiting					
	.535			.535	x	100	=	53.5	gr.
	x	.158		Kaolin					
		.158	.316	.158	x	258	=	40.5	gr.
		x	.760	Flint					
			.760	.760	x	60	=	45.5	gr.
			x						

STEP 4. After the glazes are tested, the results are analyzed and plotted systematically on the appropriate axis, and graph for each test. Four qualities are of interest.



mat

bright

opaque

transparent

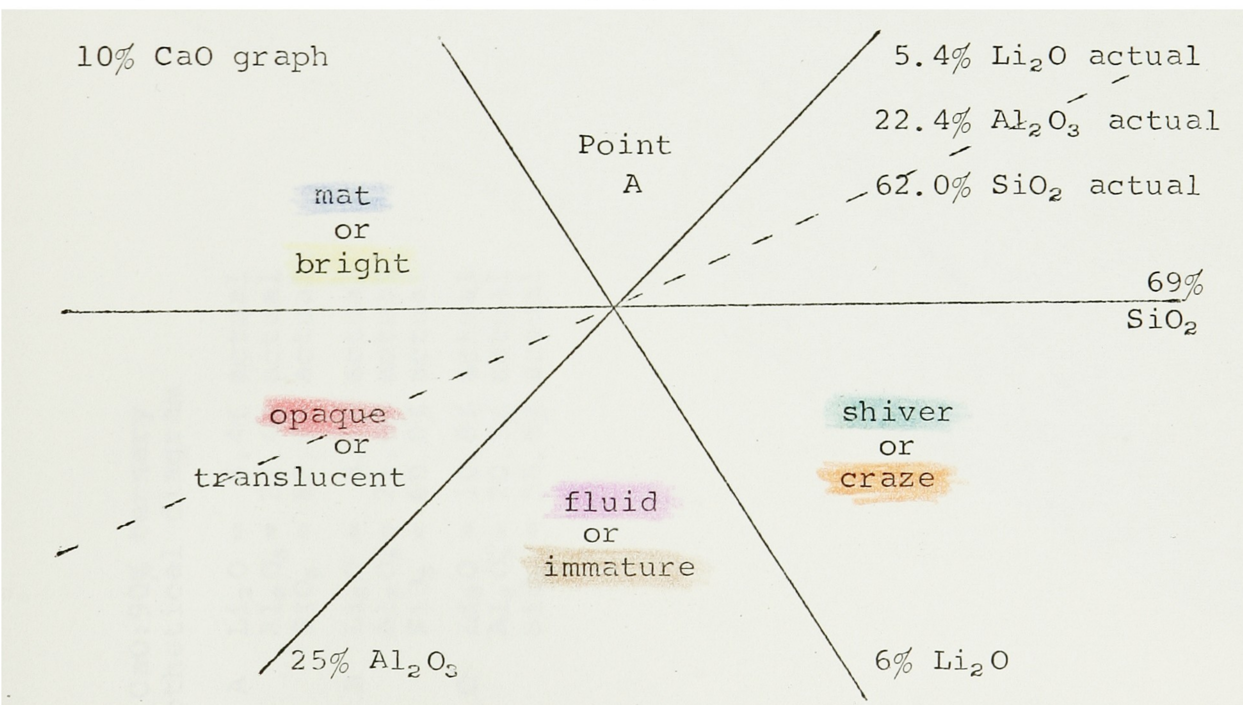
shiver

craze

immature

fluid.

In order to illustrate what I have in mind, I shall plot a hypothetical graph for each of the points and percentages diagrams used. This will illustrate why more points need to be used to add a broader perspective to what could be happening over the whole region. I have enlarged this to make my point in a so-called 40% CaO diagram. Below is a detail of a point from the graph to illustrate how each point shall be plotted graphically.

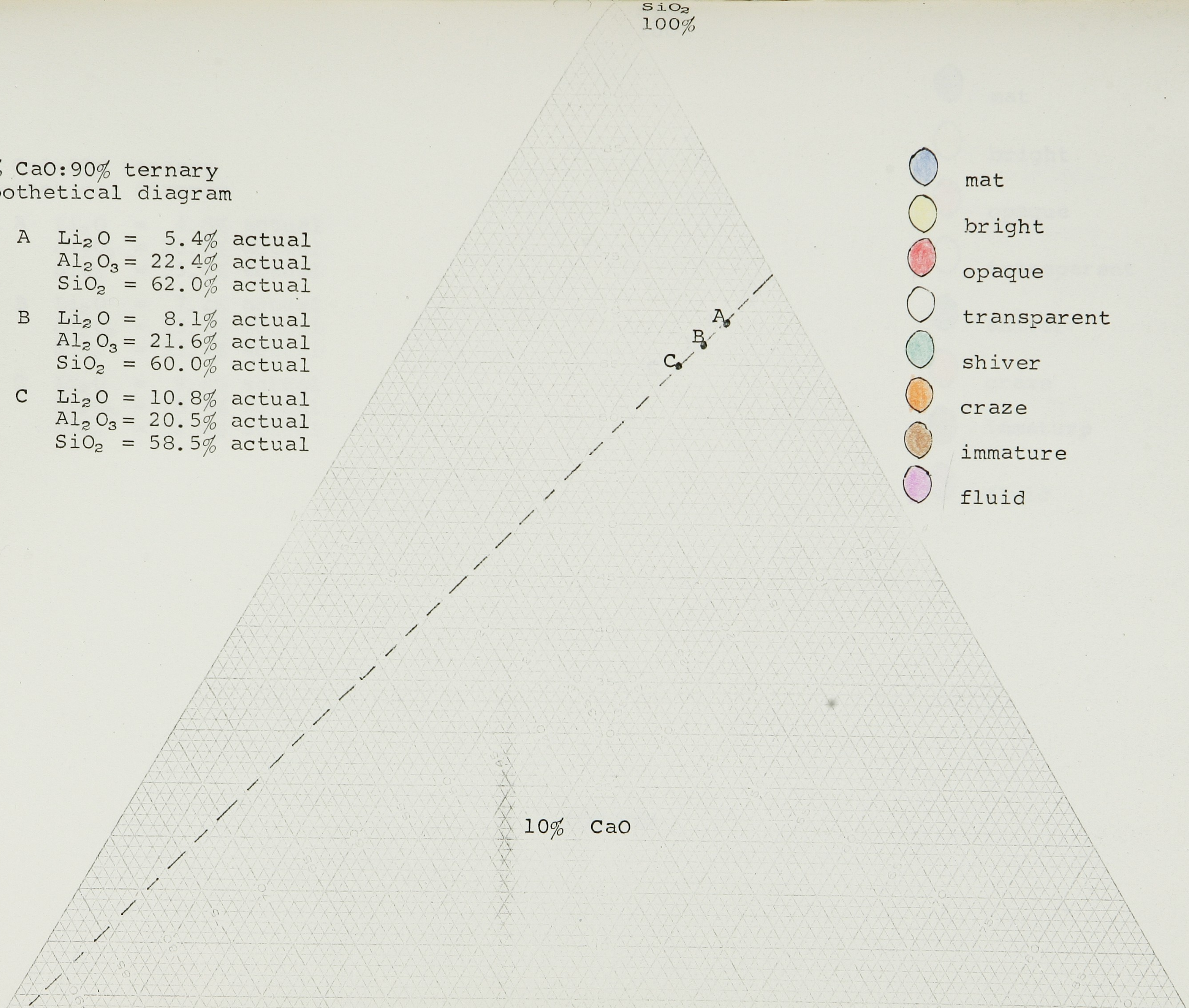


10% CaO:90% ternary
hypothetical diagram

pt. A Li_2O = 5.4% actual
Al_2O_3 = 22.4% actual
SiO_2 = 62.0% actual

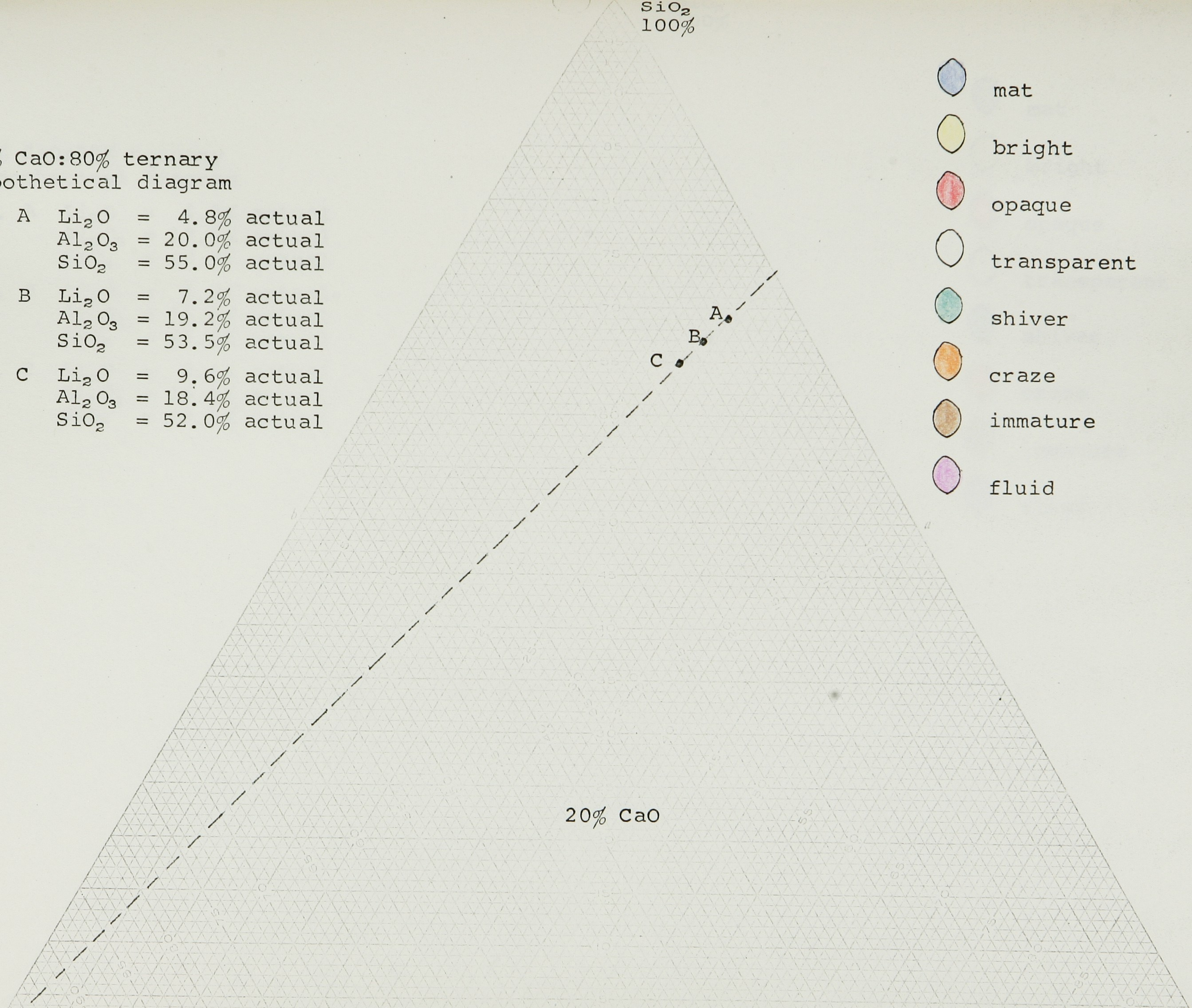
pt. B Li_2O = 8.1% actual
Al_2O_3 = 21.6% actual
SiO_2 = 60.0% actual

pt. C Li_2O = 10.8% actual
Al_2O_3 = 20.5% actual
SiO_2 = 58.5% actual



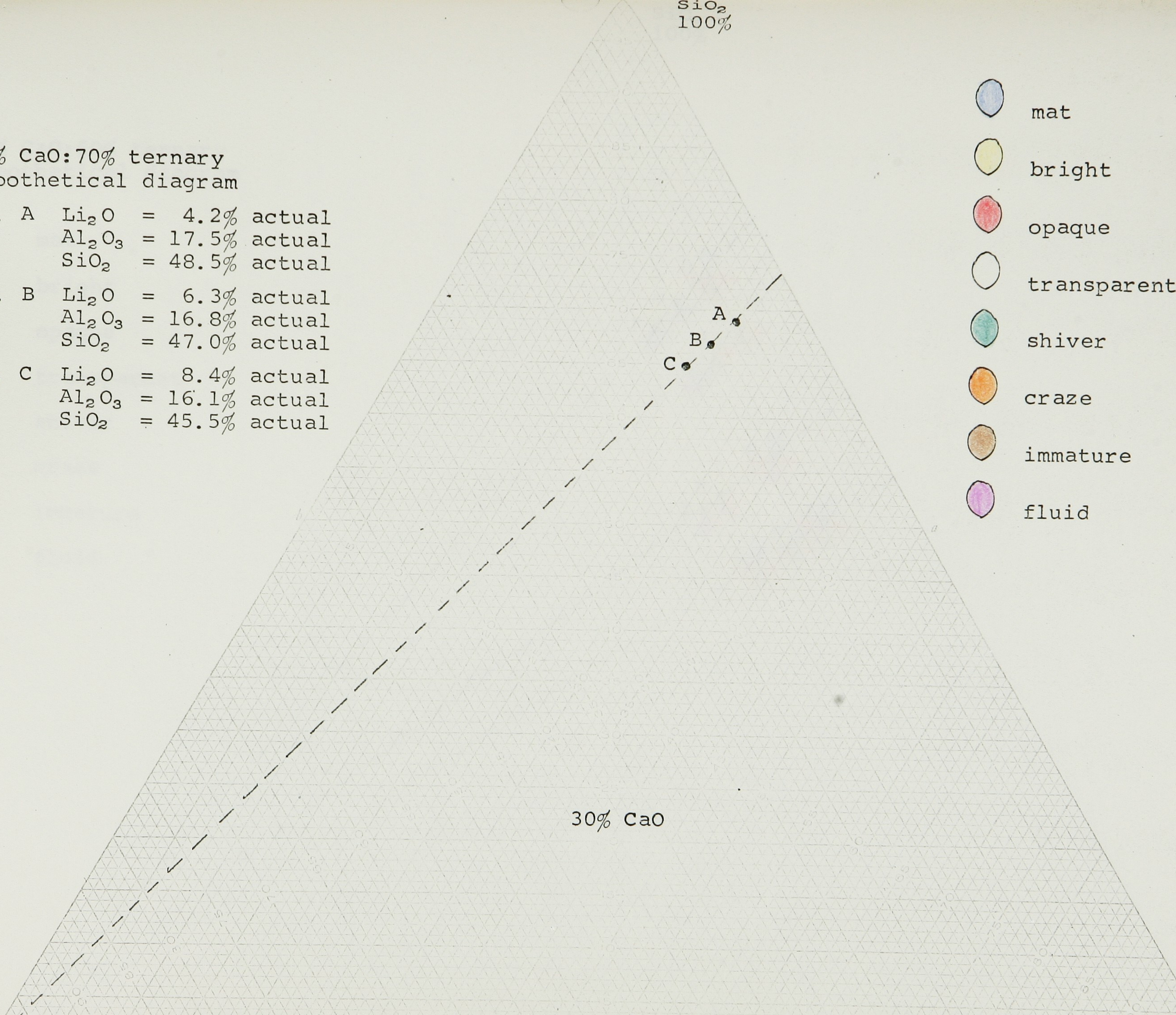
20% CaO:80% ternary
hypothetical diagram

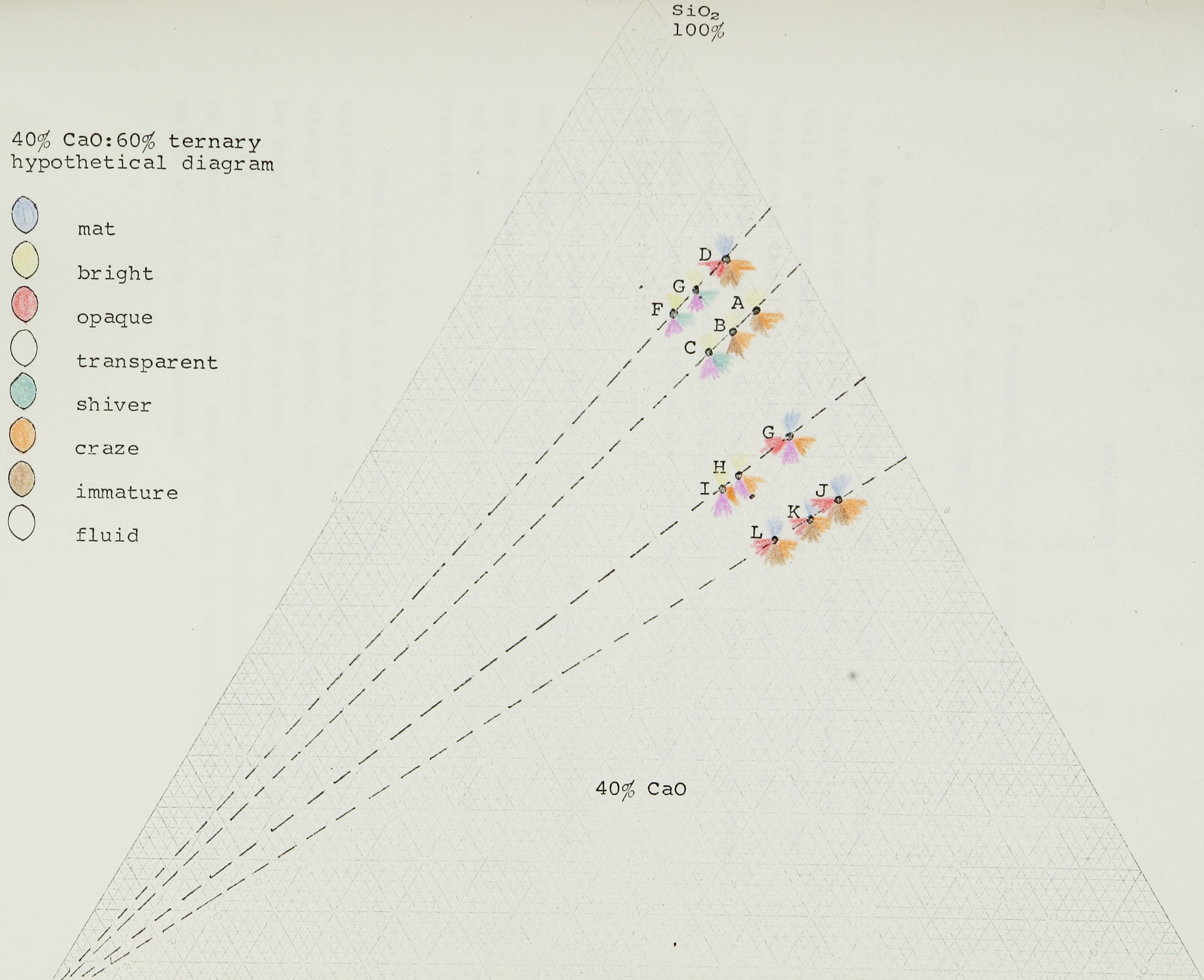
pt. A	Li_2O	=	4.8%	actual
	Al_2O_3	=	20.0%	actual
	SiO_2	=	55.0%	actual
pt. B	Li_2O	=	7.2%	actual
	Al_2O_3	=	19.2%	actual
	SiO_2	=	53.5%	actual
pt. C	Li_2O	=	9.6%	actual
	Al_2O_3	=	18.4%	actual
	SiO_2	=	52.0%	actual



30% CaO:70% ternary
hypothetical diagram

pt. A	Li_2O	= 4.2%	actual
	Al_2O_3	= 17.5%	actual
	SiO_2	= 48.5%	actual
pt. B	Li_2O	= 6.3%	actual
	Al_2O_3	= 16.8%	actual
	SiO_2	= 47.0%	actual
pt. C	Li_2O	= 8.4%	actual
	Al_2O_3	= 16.1%	actual
	SiO_2	= 45.5%	actual





40% CaO:60% ternary
hypothetical diagram
mat
bright
opaque
transparent
shiver
craze
immature
fluid
SiO2
100%
D
G
F
A
B
C
G
H
I
J
K
L
40% CaO

APPENDIX F

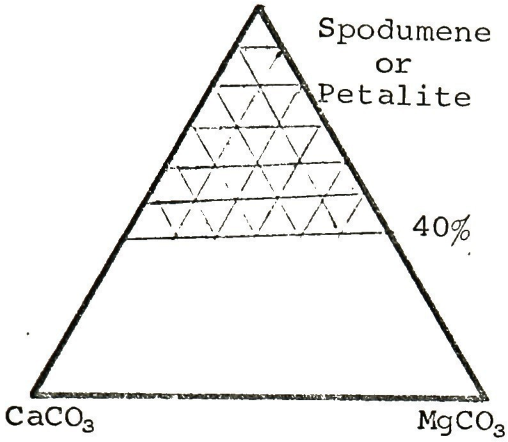
A Systematic Use of a Natural Lithia for Glaze Computation and Analysis

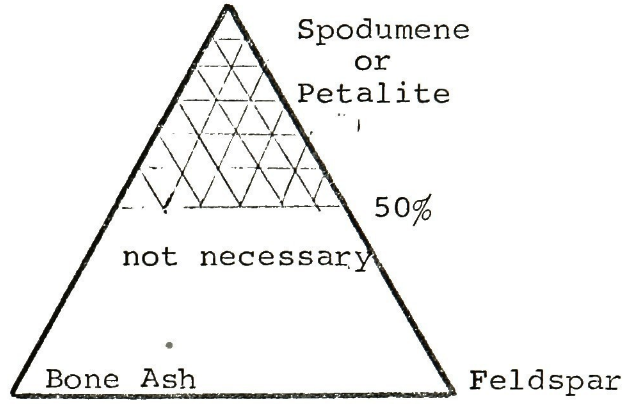
Spodumene and petalite can be thought of as a fixed lithia:alumina:silica ratio with a trace of impurities. This is extremely convenient. Use of these compounds can eliminate the lithia ternary phase diagram and the adjustments necessary to keep the three elements in the same ratio together when the fourth member oxide content is changed. Instead there are just two raw materials to vary one to the other.

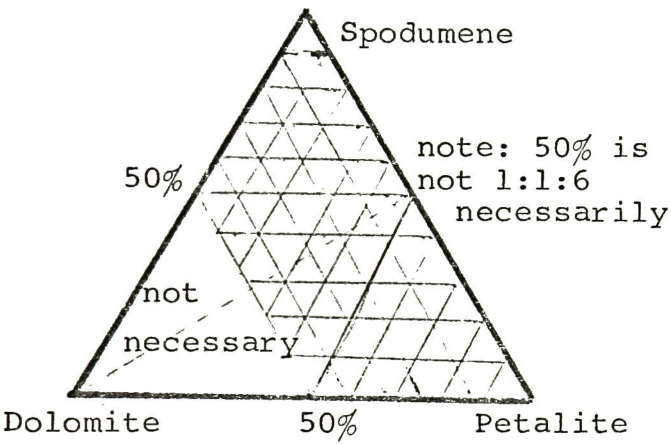
The triaxial diagram can then be used in a different way, also, namely, to allow the use of a fifth oxide. This system can also include even more oxides (through use of feldspars, etc.) and a sensible graphic analysis still results.

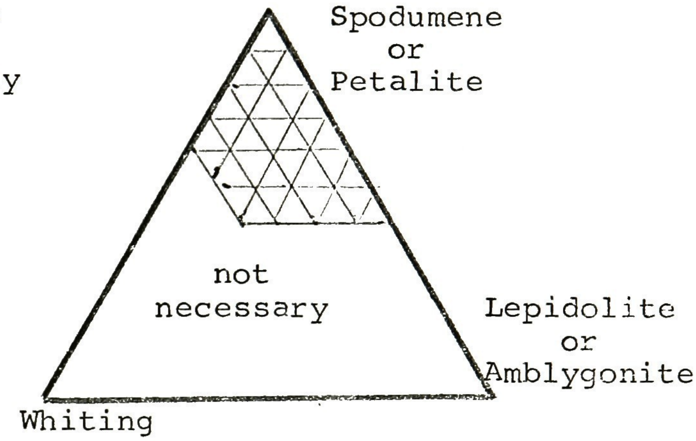
The triaxial is set up so that the percentages are the weights actually used for the glaze tests, so the glaze always totals 100 parts. Since the lithia mineral should be kept high in the glaze, there is no reason to go below 50% of the lithia mineral until results indicate the need to correct a crackle. What follows is a variety of examples which would be of interest.

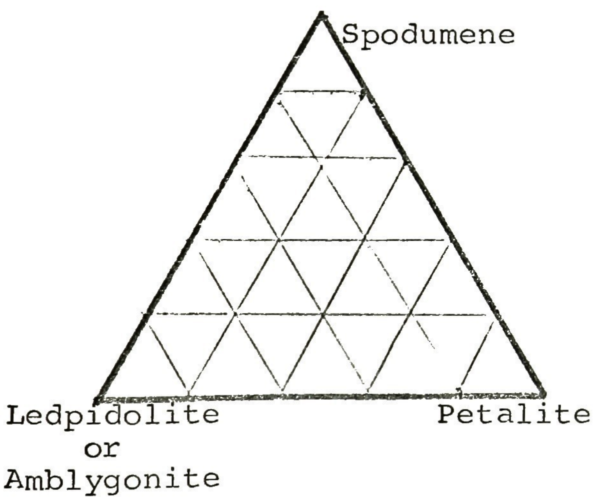
Pure oxide used first: $MgCO_3$, $CaCO_3$, ZnO, $BaCO_3$, and then use other materials.

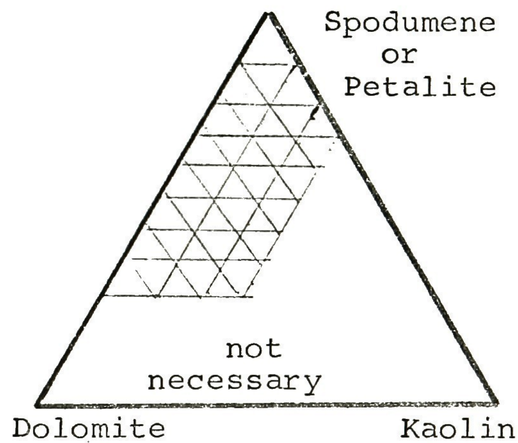












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